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SYSTEM ANALYSIS OF GELLED SPACE-STORABLE PROPELLANTS

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FOREWORD

Contract NAS7-473, "System Analysis of Gelled, Space-Storable Propellants," is being performed by the Aerojet-General Corporation at Sacramento, California. This interim report describes accomplishments for the first year of the contract, from May 1966 through April 1967.

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I. INTRODUCTION

A. OBJECTIVE

The objective of this study was to establish the systems aspects of the use of gelled, space-storable propellants in spacecraft engine systems. The effort was directed toward assessing the potential of this type fluid and identifying the design requirements. The analysis considered passive storability, zero gravity control, expulsion, sloshing, ignition, multiplicity of restarts, propellant utilization, throttlability, performance, heat transfer, and other system design aspects.

Gelled (non-metalized) propellants are of interest because of preliminary indications that gelling liquid propellants for use on space missions may provide several system advantages. Zero-g propellant position control may be obtainable by gelling so that positive expulsion devices can be eliminated. Liquid sloshing forces, which would impair system performance, may be significantly reduced by gelling. Gelling the propellants may allow the use of laminar-flow injectors which can be deep throttled with less loss of pressure drop than in laminar Newtonian flow. The hazards accompanying a cryogenic propellant spill can be greatly reduced by gelling, which will both confine the spill to its original location and greatly reduce its rate of vaporization, the latter minimizing the toxicity and fire problems.

B. APPROACH

The study was divided into four technical tasks: preliminary investigation, preliminary analysis, component design analysis, and system design analysis.

1. Task I--Preliminary Investigation

The preliminary investigation consisted of (1) reviewing existing available information regarding gelled propellants, (2) defining the desirable characteristics of gelled propellants, (3) comparing the characteristics of available gelled propellants with the previously defined desirable characteristics, (4) selecting the most suitable gelled propellant combination for use in the Task II, III, and IV efforts, and (5) suggesting possible modifications that might be made to the propellants to make their properties more closely approach those of the desirable characteristics.

2. Task II--Preliminary Analysis

Utilizing the propellants selected in Task I, the preliminary analysis consisted of (1) investigating the effects of long-term (up to two years) space storage, (2) comparing the pressure drops in a gelled propellant system with those of the neat fluids, (3) analyzing the effects of heat transfer on the thixotropic properties of the selected propellants, and (4) analyzing the fluid flow transient conditions encountered with the use of gelled propellants.

3. Task III--Component Design Analysis

Using the selected propellants, the component design analysis consisted of (1) investigating the available means of propellant expulsion and control, (2) investigating methods of flow control and determining the effects of gelled propellant on flow rate, response time, pulse width, pulse width control, repeatability, etc., (3) investigating means of throttling rocket engines and determining the most suitable method, (4) determining the effects on injector design due to the use of gelled propellants, and (5) analytically determining the vacuum performance of the propellants.

4. <u>Task IV--System Design Analysis</u>

On the basis of the results of the preceding tasks, a preliminary design analysis was made for three propulsion systems using gelled propellants to perform (1) Lunar Descent Mission from orbit to surface with a 17,500-lb propellant capacity, (2) Lunar Ascent Mission into orbit from surface with a 5000-lb propellant capacity, and (3) Space Probe Mission with a 13,000-lb propellant capacity, which can provide a 7500 ft/sec ideal velocity increment after a 15-month space storage.

From a systems aspect, a summary of the advantages and disadvantages for the use of gelled propellants was prepared for each mission studied.

C. TERMINOLOGY AND DEFINITIONS

<u>A Glossary of Rheological* Terms</u> (ASTM D 2507-66T) is provided as Appendix A to clarify the meanings of the terms used to describe non-Newtonian flow. Most gels are shear-thinning fluids which are pseudoplastic (non-time-dependent) or mildly thixotropic (time-dependent thinning). Usually the shear-thinning characteristic of the gel (not time-dependent) is the dominate flow property, and the thixotropic property is minor or nonexistent. The latter case is defined as the shear-thinning pseudoplastic. To refer to gels in general as thixotropic or thixotropes is misleading and often wrong in light of the definitions adopted in ASTM D 2507-66T.

Although stated in somewhat different terms in the Glossary, shear-thinning refers to the phenomina in which the ratio of shear stress

*Rheology-The science treating the deformation and flow of matter.

to shear rate of the gel decreases as the flow rate increases (laminar flow only). In laminar, Newtonian-flow, the ratio of shear stress to shear rate is the viscosity. Often the Newtonian parameters for viscosity are applied to gelled propellants, but are termed "apparent viscosity." The term "apparent viscosity" is used describing macroscopic flow behavior for gels in comparison to Newtonian fluids but has no derivation or correlation with Newtonian flow theory.

Thus, to define shear-thinning in less correct but more understandable terms, the laminar "apparent viscosity" decreases as the flow rate (shear rate) increases. This is an important characteristic of gelled propellants and is discussed in detail in relation to deep throttling systems.

D. REPORT FORMAT

Most of this study is reported in Volume 1 of this report (UNCLASSIFIED volume). Classified data, including abstracts from the gel technology literature review, are reported in Volume 2 (CONFIDENTIAL volume). The introductory section is identical in each volume.

E. NOMENCLATURE FOR SUBJECT GELS

The properties of gelled OF_2 were estimated wherever possible from cryogenic gel data. This propellant has been designated GOF_2-E1, "G" for gelled and "E1" for estimate one. Most of the properties of GMMH-S1 ("S1" for simulant one) were taken from data for gelled MHF-3. Since MHF-3 is 86% MMH and 14% N_2H_4, it was assumed that the properties would be very similar for GMMH. The terms estimate and simulant are an indication of data confidence.

It was anticipated that simulant-two or estimate-two propellants might become necessary as the work developed. GOF_2-E2 (9.2% ClF_5 gelling agent) later replaced GOF_2-E1 (3.4% LiF) but the same basic physical properties were estimated so they can be used interchangeably with respect to density, freezing point, yield stress, flow properties, etc.

II. SUMMARY

A. TASK I --PRELIMINARY INVESTIGATION

1. Literature Review

A literature search was made for gelled propellant technology. Approximately 400 technical reports were surveyed to determine those most applicable to the areas of interest on this contract. Reports on ungelled propellants were not considered of interest except for comparison where the same propellant system has been gelled. Of the above reports, half were considered directly useful to this contract and these have been abstracted. The abstracts are included in Volume 2, Appendix A. The report Bibliography appears as Appendix B in Volume 1.

2. Definition of Desirable Propellant Characteristics

Desirable gelled propellant characteristics were defined from a systems aspect for four main areas: performance, storability, rheological properties, and logistics.

The desired performance was the same as for neat propellants: high specific impulse and bulk density, low combustion and expansion losses, and smooth, hypergolic ignition.

Storability requirements were similar to those of neat propellants, i.e., a wide liquid range and good material compatibility, with the added requirements for gels of minimum gel separation, bulk growth and sloshing, good zero gravity position control (without positive expulsion) and micrometeoroid puncture leak-sealing capability.

The desired rheological properties of gelled propellants provided the most obvious examples of conflicting demands caused by this approach to alleviate some of the problems typical of neat propellants:

(1) High yield stress for good slosh, position and mechanical stability against low yield stress for low line pressure drops.

(2) A gel residue capable of cementing over micrometeoroid punctures as opposed to no residue in the injector manifold and orifices when restarting in space.

Thus, rheological properties will involve tradeoffs which will usually sacrifice some pressure drop to reduce slosh and eliminate positive expulsion devices and will maintain free flowing restartable injectors as a primary necessity.

Desired handling requirements were the same as those for neat propellants with regard to toxicity, contamination sensitivity, flammability and shock hazard. Desired utilization requirements were also similar to neat propellants, except that a cohesive (nonwetting) property was added.

Desired logistics were the same as for neat propellants: low cost and readily available, plus the added minimum mixing requirement.

3. Propellant Evaluation

The comparison of the actual gelled propellant properties with the desired or "ideal" gelled propellant properties was rather unsatisfactory because of the lack of actual data for most space-storable propellants. The problem becomes apparent when looking at Table 2 of Volume 2, Appendix A.

Most of the individual propellant effort has gone into metalized earth storables and even for them the only gelled propellant which is really well characterized is Alumizine. In general, much of the storable effort appears to have been diluted by trying many gelling agents with many propellants while developing gel technology. With the basic gel technology partially developed and some data for cryogenic gels available, the system design work from this contract should help select the areas in which further gel development should be concentrated. It will also show any unexpected effects of properties on system designs.

4. Propellant Selection

On the basis of previous neat propellant performance analyses for the three missions of interest, seven representative, high performance propellant combinations were selected for evaluation as gelled propellants. Each propellant was assumed to be gelled with what appeared, at the time, to be the most suitable gelling agent for that particular propellant, and theoretic performance calculations were made. Using an abbreviated interaction theory analysis, the delivered (predicted) performance for each propellant combination was estimated and used in a mission performance calculation along with system hardware characteristics that were based on previous studies of the three missions, Lunar Descent, Lunar Ascent, and Space Probe. The mission performance calculation rated the propellants by the fraction of payload-weight to vehicle-launch-weight.

The best performing propellant combinations for the Lunar Missions were gelled LF_2/LH_2 and gelled LF_2/N_2H_4 blend*. For the Space Probe Mission, the best mission performances were obtained with gelled LF_2/N_2H_4 blend* (if storable) and gelled OF_2/B_2H_6. The former combination owed its high mission performance to the assumption that 15-month space storability of gelled LF_2 could be obtained without boiloff.

*67% N_2H_4 + 24% MMH + 9% H_2O

The propellant combination selected for the system analysis and design tasks in the remaining three quarters of this contract is gelled OF_2/MMH. A comparative performance analysis, space storability, and current gel development activity were the selection criterion. The selected propellants were assumed to be gelled with 3.4% LiF for the OF_2* and 1% Colloid 8010** for the MMH. Later the OF_2 gelling agent was changed to 9.16% of frozen submicron particles of ClF_5 to improve performance and avoid residue problems.

5. Suggested Properties Modification

The method of modifying the properties of a gel always comes back to making some kind of a change in the gelling agent, either by changing agents, increasing or reducing its concentration, changing its particle size or distribution of sizes if it is a particulate agent, or by combining more than one agent to get specifically desired properties. Unfortunately, while basic trends are known, the determination of the best gelling agent is essentially a trial and error task.

B. TASK II--PRELIMINARY ANALYSIS

1. Selected Propellant Properties

Both physical and rheological properties were selected for gelled OF_2 and gelled MMH. Whenever possible, actual measured values were used. In other cases the properties of the neat propellants were corrected for the addition of the gelling agent. In a few cases, it was necessary to estimate properties from similar propellants, such as MHF-3 for MMH and LO_2 and LN_2 for OF_2.

*OF_2 gelling with LiF particles was in progress under Contract NAS 3-6286, Gelling of Cryogenic Oxidizers, Reaction Motors, Denville, New Jersey.
**Colloid 8010, a modified galactomannan from Stein, Hall & Co., New York, New York. Metalized MMH gelling under Contracts: NOw 65-0575-c, NOw 63-0740-c, etc.

2. Comparative Pressure Drops

Pressure drops were compared for typical pressure-fed propulsion systems using neat and gelled propellants. System pressure drops were estimated on the basis of very incomplete data. The pressure drops for the gels were arbitrarily taken to be 50% higher to assure an adequate allowance.

3. Long-Term Storage

Long-term storage of the selected propellants was investigated under four categories: liquid-gel separation, bulk growth, effect of aging on yield stress, and material compatibility. Similar properties for related propellants were reviewed and discussed. It was concluded that (1) liquid-gel separation would be less of a problem in space than on earth (low gravity), (2) bulk growth should not be a problem in the nonmetalized propellants (little contamination), and (3) material compatibility is not affected by gelling the propellants (inert or similar gelling agent). Change in yield stress with time is considered a potential problem.

4. Heat-Transfer Effects

The regenerative-cooling potential of gelled propellants was estimated from some inconclusive alumizine tests. Temperature gradients across space-stored spherical, gel-storage tanks were calculated, and the thermal protection required to prevent OF_2 from boiling off or MMH from freezing was estimated.

5. Fluid-Flow Transients

A method was developed for simulating the non-Newtonian flow of gelled propellants in the 109 Engine Transient Computer Program. Typical transients are shown comparing performance of an Apollo-type engine with gelled and ungelled propellants. It was concluded that differences in starting, stopping, and throttling transient performance between gelled and neat propellants were minor and, if desired, could be easily eliminated by changes in the timing or characteristics of the valves.

C. TASK III--COMPONENT DESIGN ANALYSIS

1. Propellant Expulsion and Control

a. General

The effect of gelling the propellants was considered for the operation and selection of positive expulsion devices, the weightless equilibrium propellant position, and expulsion efficiency. Positive expulsion diaphragms, bellows, etc., should operate as effectively with gels as with neat (non-gelled) propellants. Gel structure will maintain gel position during weightlessness and against low adverse acceleration (0.1g) unless vibration effects it significantly. Contoured tank bottoms have demonstrated high expulsion efficiencies, but may possibly be avoided if full-scale outlet baffles prove effective.

b. Gel Slosh Tests

Slosh tests were performed with neat water and water gelled with 0.27% Carbopol 940 (an organic gelling agent) and 5.2% Santocel Z (sub-micron SiO_2 particles). Resonant frequencies were determined for each fluid in an 18-in.-dia acrylic tank suspended from two long cables. Tests were performed with the tank 30 and 70% full. The resonant frequencies for the gels occurred at higher values than for water and their slosh modes differed from water and each other. Gel motion decayed in two cycles or less compared to 30 to 40 cycles for water. Superimposed high frequency (5 to 100 cps) did not appear to affect the gel slosh modal behaviors.

c. Screen Containment and Expulsion Tests

The water gels used in the slosh tests were also used for the containment and expulsion tests. The gels were contained by and expelled through several screens ranging from 18 to 100 mesh. Screens appear to be suitable for containing gels against several g's acceleration, but expulsion efficiencies through screens were very poor because the pressurizing gas cored through the gels to the outlet.

A baffle across the gel outlet of a flat-bottomed tank reduced the residual to 50% or less of that left by expulsions without baffles in the tank.

2. Flow Control

The use of gelled OF_2 and gelled MMH requires no innovations in systems or controls. It was concluded that the controls for gelled propellants would be essentially the same as those for the neat liquid propellants. Leakage will not be aggravated by the use of gelled propellants without metal additives and may in fact be less of a problem than with liquids. The use of gelled propellant for valve actuation is possible; however, bleed-in and cleaning will be more difficult. Decontamination and cleaning of controls is a potential problem especially for particulate gelling agents.* Experience to date indicates that proper internal design and contouring of parts in conjunction with use of a suitable solvent will minimize cleaning difficulties.

*Particulate gelling agent: submicron particles of a solid material.

3. Injector Design and Throttling

Preliminary designs were made for conventional triplet injectors for the fixed thrust and shallow throttling missions*: single-thrust-chamber space probe, lunar ascent, and three-thrust-chamber space probe. A momentum exchange triplet injector was designed for the deep throttling (11:1) lunar decent mission. The triplet pattern was selected on the basis of the availability of gel test data so that a comparative performance analysis could be performed. Advanced injection concepts such as a laminar flow, HIPERTHIN platelet injector, or a gas-gas combustion cycle are considered more desirable than the triplet configuration analyzed, but no non-metalized gel performance data were available for either of these concepts.

4. Performance

Predictions of delivered performance were made for neat and gelled OF_2/MMH in four thrust chamber designs using the "Interaction Theory" method of analysis. The predicted performance of (OF_2 + 3.4% LiF) and (OF_2 + 9.16% ClF_5) with (MMH + 1% Colloid 8010) were calculated for both the present triplet injectors for which the preliminary designs were made and the future platelet injector concept.

A nominal chamber pressure of 100 psia was used for each thrust chamber and a minimum length Rao (bell) nozzle was used with an exit expansion ratio of 40:1.

The predicted future performance at 100 psia ranged from 366.9 sec (92.49%) for the 13,000 lbf chamber to 350.0 sec (88.24%) for the 2670 lbf chamber for the neat propellants. Gelling the propellants reduced the predicted specific impulse by about 2.4-2.5% for OF_2 gelled with inert

*Shallow throttling, 3:1 or less.

LiF but only reduced the performance by about 1.2-1.4% with the energetic ClF_5 gelling agent in the OF_2. Approximately three times the expected requirements of ClF_5 was used to insure a conservative calculation in lieu of test data for the particular propellants.

D. TASK IV--SYSTEM DESIGN ANALYSIS

Preliminary system designs were made for a lunar descent and lunar ascent mission to compare payload capabilities using neat (non-gelled) and gelled, but not metalized, OF_2/MMH. Several designs were analyzed for each mission to determine the effect of advanced injector concepts and the amount of ClF_5 gelling agent in the OF_2 on the delivered payload. Conventional orificed injectors were compared with HIPERTHIN platelet injectors and 3.05 and 9.16 wt% frozen ClF_5 particles were used to gel the OF_2. These gels were designated GOF_2-E2 and GOF_2-E3, respectively. The lunar descent and lunar ascent designs are discussed in Volume 2 of this report.

For the space probe mission, preliminary designs were made for a single engine configuration and a shallow-throttling three-engine configuration. As with the lunar missions, HIPERTHIN platelet injector concept was compared with conventional orificed injector and the effect of gelling agent (ClF_5) concentration in the OF_2 was investigated. In each instance, a comparison was made between the gelled OF_2/MMH delivered payload to evaluate overall system performance.

The HIPERTHIN platelet injector concept is proprietary to the Aerojet-General Corporation and patents have been applied for.

III. TECHNICAL DISCUSSION

A. TASK I--PRELIMINARY INVESTIGATION

1. Literature Review

Hand and computer searches for gelled propellant information were made of the Aerojet-General Technical Library at Sacramento and the Corporate Technical Information Center (Von Karman Center, Azusa), Chemical Propellant Information Agency (CPIA), Defense Documentation Center (DDC), and National Aeronautics and Space Administration (NASA).

Nearly 1000 references were initially obtained in the literature review. A quick screening of abstracts reduced this list to approximately 400. This final report-bibliography is presented in Appendix B. The bibliography uses an open ended numbering system in which each report was added to the end of each alphabetical section with the first letter of the title determining the section. For example, the seventeenth report placed in the "F" section, Feasibility of a Tripropellant Feed System, is called out as Reference F17. Any reference of this letter-number form will be found in the Appendix B, bibliography in the back of this volume. The customary number references are used for reports not contained in the bibliography and these references can be found at the end of the text.

Approximately 200 of the most applicable reports found during the literature review were abstracted for pertinent data. These abstracted data are presented in Appendix A, Volume 2 of this report (classified volume) and are cited by the above letter-number reference technique. Tables 1 and 2 of Appendix A, Volume 2 summarize the theoretical and experimental performance data with gelled propellants and the available data on individual propellant properties, respectively.

The discussion of the findings of the gelled propellant technology literature survey are presented in Volume 2, Section III,A,1 of this report.

2. <u>Definition of Desirable Propellant Characteristics</u>

The desirable characteristics for gelled propellants are listed in Table 1. Many of these characteristics would be desirable for any propellant system. For example, under the heading "Performance," high specific impulses, high density, good combustion efficiency, hypergolicity, and smooth ignition are desirable for any system. Low cost, high availability, good material compatibility, low toxicity and nonsensitivity to shock are likewise always desirable.

It is in the area of rheological properties, storability, and propellant utilization that requirements unique to gels became apparent. Unfortunately, some of the desirable rheological properties are in direct conflict. For instance, a high yield stress is desirable for minimum gel separation, minimum slosh, maximum mechanical stability, good leak sealing, position stability, and low boiloff rate. On the other hand, low yield stress is desirable to reduce pressure drops, to reduce pumping or pressurization feed system requirements, to minimize mixing requirements, and to improve propellant utilization. The specific requirements of a particular mission must be used to define a compromise among these several factors.

The high-shear viscosity must be low so the gelled propellants can be used in conventional liquid rocket engines. It is desirable that the shear rate-shear stress relation approach that of a Newtonian fluid and have minimum temperature sensitivity.

In general, the desirable values given in Table 1 are guides for improving gelled propellant performance, rather than absolute limits for rating their usefulness. In order to accurately rate gelled propellants, a particular mission must be specified.

3. Evaluation of Available Gelled Propellants

Alumizine is the only gelled propellant available today for which there is sufficient published data to accurately rate it aginst the more than 30 desirable characteristics listed in Table 1. However, the following sections will discuss the data that are available for the other propellants of interest.

a. Cryogenic Propellants

(1) Performance

Gelling the cryogenic propellants causes very little change in performance except to reduce the specific impulse by the amount of the inert material in the gelling agent. Those systems which are hypergolic remain so after gelling, and those which are not, do not become so. In general, the gelling agents being considered for LH_2 (Li, $LiBH_4$) are themselves good fuels and cause minor reductions in performance, while the gelling agents being considered for the oxidizers (LiF, SiO_2) are inert materials which reduce performance directly proportional to their concentration.

In one metal-loaded, cryogenic gel both density and specific impulse are increased since the effect of the metal loading far outweighs the small percent of particulate gelling agent required.

(2) Storability

Gelling does not significantly affect the storability of all of the cryogenic systems considered. The gel structure apparently provides a capillary or wick effect for the migration of molecules to the propellant surface which compensates for eliminating convection currents in the storage tanks. Gelling reduces the boiloff rate when cryogenic propellants are spilled because the gel structure minimizes spreading and contact with ambient surfaces.

(3) Rheological Properties

There is insufficient yield stress or pressure drop data for cryogenic systems to effectively rate them.

(4) Logistics

Gelling cryogenic propellants undoubtly increases the cost, but to date this has been done on such a limited scale that no conclusion can be drawn.

b. Metalized Propellants

(1) Performance

The metalized propellants were developed to improve the performance of the neat propellants. Adding a high-energy solid to neat fuels always improves the density and in most cases improves the specific impulse as well. The gelling agent concentrations required for the amine fuels (N_2H_4, MMH, MHF-3) is so small (1%) that performance degradation from this source is negligible.

(2) Storability

Metalizing the neat fuels tends to reduce their storability. The solid additives must be prevented from settling, and the heterophase, multicomponent systems are less chemically compatible than the neat fuels. Gelling can improve the space storability of these systems, however, by reducing slosh, improving leak sealing, and increasing position stability. With the possible exception of N_2O_2/Beryllizine, the metalized propellants have not been considered for space storable missions.

(3) Rheological Properties

The metalized systems require sufficient gelling agent to keep the solid additive from settling and thus, in general, have higher yield stresses, greater high shear viscosity, and thus greater pressure drops than the nonmetalized gels. Again, however, this does provide better slosh reduction, position stability, and leak sealing.

(4) Logistics

The high cost of all the solid additives considered, excepting aluminum, has greatly increased the cost of metalized gelled propellants. For those systems using aluminum powder, the cost has actually been reduced somewhat.

c. Other Propellant Systems

(1) Performance

In general, performance was reduced only by the difference in energy between the gellant and the propellant.

(2) Storability

The very limited data reported indicated that storability was uneffected by gelling except for the usual slosh, leak sealing, and position stability improvement.

4. Propellant Selection

a. Method

The purpose of this subtask was to select the most suitable space-storable gelled propellant combination for use in the system studies which were performed during the remaining three quarters of the contract. The three missions which were studied are: (1) lunar descent with 17,500 lb of propellant, (2) lunar ascent with 5000 lb of propellant, and (3) a space probe carrying 13,000 lb of propellant, space-stored for 15 months, and delivering an ideal velocity increment of 7500 ft/sec.

A performance study was made by reviewing existing propellant selection studies for neat (not gelled) propellants, selecting representative neat propellant combinations, estimating their performance as gelled propellants, and comparing their performance capabilities in terms of the three missions being studied. While the performance study points out propellants of interest, the final selection of the most suitable gelled propellant combination for further study was based primarily on the availability of gel experience and flow data for the propellants.

b. Initial Propellant Screening

The High Performance Apollo Propulsion System Study, Reference 1, which rated neat propellant combinations and then selected the best neat propellant combination for a 1970 and a 1975 operational Apollo vehicle, was used as the initial source for propellants to be selected for evaluation for the lunar missions. This study considered performance, reliability, operational aspects, development ease, and launch operation ease.

The most applicable evaluation of neat propellants for the Space Probe Mission was found in Reference 2. This study ranked 71 propellant combinations on the basis of the fraction of delivered-payload-weight to vehicle-loaded-weight. It assumed a mission with an ideal velocity increment 10,000 ft/sec, and the following system characteristics: 3% ullage, 1% outage, a nonvolume dependent-weight to vehicle-weight fraction of 0.015 lb/lb and a volume-dependent-weight to tank-volume fraction of 7.0 lb/ft^3. These system characteristics were considered representative of a pressure-fed propulsion system with an ablative chamber.

The study found that LF_2 or FLOX with N_2H_4, B_2H_6, LH_2 or MMH were the highest performing neat propellant combinations followed by OF_2 with similar fuels.

On the basis of the above two propellant selection/mission analysis studies, the following neat propellant combinations were selected for evaluation as gelled propellant systems:

LF_2/LH_2
$LF_2N_2H_4$ Blend*
LF_2/B_2H_6
OF_2/B_2H_6
OF_2/MMH
OF_2/C_3H_6 (propylene or propene)
FLOX-73.3**/0.52 C_3H_6 + 0.48 C_3H_8

* 67% N_2H_4 + 24% MMH + 9% H_2O
**73.3% LF_2 + 26.7% LO_2

The propellant combinations selected for evaluation as gels represent each of the families or classes of propellant combinations which rated highly in the referenced performance studies. The particular combination chosen to represent each family was based on system operation considerations. For example, a hydrazene blend with lower freezing point and greater high temperature thermal stability was selected over undiluted N_2H_4 to represent the LF_2/amine family. The fuel mixture 0.52 C_3H_6 + 0.48 C_3H_8 was selected because it is still liquid at the normal boiling point of FLOX-73.3, about 155°R, (Reference 3).

c. Gel Composition and Properties

Gelling agents were selected for the propellants on the basis of good chemical compatibility and minimum performance loss.

All of the oxidizers were gelled with particulate gelling agents because organic gelling agents would not be compatible. Data from liquids gelled with Cab-O-Sil H5, 0.007 micron particles of pyrogenic silica (SiO_2), indicated that 2% by volume caused gel formation regardless of the liquid being gelled (Table 2). However, since Reference (G 12) indicates that SiO_2 is not shock stable in OF_2, while freeze-dried LiF is shock stable, it was assumed that 0.007 micron particles of LiF can be produced and that they will gel LF_2, FLOX -73.3 and OF_2 at a concentration of 2 vol %.

Later in the program some performance calculations were added for an improved OF_2 gel. This high performance gel used 2 vol% submicron particles of frozen ClF_5 (9.16 wt %).

Similarly both LH_2 and B_2H_6 were assumed to be gelled with 2 vol% of 0.007 micron Li particles. A particulate gelling agent was required for LH_2 because any organic agent would be frozen (and therefore a particulate) at LH_2 temperatures. Li metal was selected for its fuel value. An energy contributing gelling agent is required for LH_2 because its low density results in 2 vol% being equivalent to 13.3 wt%. Li was also selected to gel B_2H_6 on the basis of its energy contribution although there may be some question of B_2H_6/Li compatibility.

The remaining fuels were gelled with organic gelling agents which are preferred over particulates because usually less is required. For C_3H_6 (proplylene or propene) and for the mixture 0.52 C_3H_6 + 0.48 C_3H_8, aluminum octoate was selected as representative of the class of soaps which have been found to be effective in gelling hydrocarbon-based fuels. The Al octoate has some fuel value and can be dissolved in these fuels at cryogenic temperatures. For the N_2H_4 blend, 2% of "CP" (an Aerojet-General Corporation proprietary gelling agent) was selected. CP has good fuel value, produces good high temperature stability, and is less sensitive to ion contamination than Carbopol.

The weight percents of the gelling agent, the densities of the neat and gelled propellants and pertinent temperature information for each propellant and propellant combination are given in Table 3. These compositions and densities were used for all three missions studied.

d. Theoretical Performance

The theoretical performance of both the neat and gelled propellants was calculated using the Aerojet-General's Chemical Composition

Computer Program which assumes shifting equilibrium. For the standard expansion from 1000 psia to 14.7 psia, the theoretical performance loss due to gelling the propellant ranged from 2.2 to 4.2% based on peak to peak comparisons rather than fixed mixture ratio comparisons. The corresponding loss range was 1.8 to 3.1% for a vacuum expansion from a a chamber pressure of 100 psia to an area ratio of 40:1. These data are shown in Table 4. The gel concentrations are the same as those shown in the preceding table. The performance of the improved OF_2 is included in the table with gelled MMH only.

e. Predicted Delivered Performance

The delivered performance of the various propellant combinations as estimated on the basis of experience with the interaction loss analysis method. This method involves the determination of friction loss, geometry loss, heat transfer loss, nozzle kinetics loss, mixture ratio distribution loss, and energy release efficiency loss. It is based on the premise that there is an interaction between chamber and nozzle losses such that these losses cannot be treated separately, as when using c* to determine combustion efficiency. The theory of the interaction loss analysis method is discussed in more detail in Reference 4 as applied to N_2O_4/AeroZINE 50 and Section III,C,4 of this volume as applied to OF_2/MMH.

For this study, the friction, geometry and heat transfer losses were considered to be the same for all propellant combinations. The mixture ratio distribution loss was considered to be negligible since proper design can minimize this loss. The nozzle kinetic loss and the energy release efficiency loss were thus the distinguishing losses between the different propellant combinations.

The nozzle kinetics loss was estimated on the basis of calculations using the theoretical shifting equilibrium combustion data and experience with these or similar propellant combinations. The energy release efficiency was used to differentiate primarily between metalized and non-metalized propellants as experience has shown mixing and combustion efficiency to be lower for metalized propellants.

As a result of these considerations, it was found that the maximum delivered specific impulse for each propellant combination occurs at a mixture ratio which is lower than its theoretical optimum. This shift in optimum mixture ratio is due to the fact that the nozzle kinetics loss reaches its peak at the stoichiometric mixture ratio, which is slightly higher than the theoretical optimum performance mixture ratio. Uneven mixture ratio distribution across the injector face would also tend to lower the mixture ratio at which maximum delivered performance will occur.

Two examples of how these losses affect delivered performance as a function of mixture ratio are shown in Figures 1 and 2. The performance of the N_2O_4/AeroZINE 50 system is well documented and its higher delivered performance at a lower than theoretically optimum mixture ratio is well known in the industry and can be predicted on the basis of the interaction loss analysis method. Figure 2 shows the predicted and theoretical performance for neat LF_2/N_2H_4 Blend. The predicted performance has yet to be verified, but is scheduled to be done within the next year. The losses which led to the predicted LF_2/N_2H_4 Blend performance are summarized in Table 5.

The estimated delivered specific impulses used for the neat and gelled propellants on all three missions are shown in Table 6. In each series of mixture ratios and specific impulses, the first set of values is for the highest delivered specific impulse predicted for the propellants with the following set of values corresponding to the delivered specific impulse at the theoretically optimum mixture ratio. The latter values were included for comparison as the mixture ratio shifts also represent changes in bulk density.

It should be emphasized that the predicted performance for these propellants are approximations. A rigorous interaction loss analysis requires that the analysis be conducted with the hardware designs being employed. Since this is well beyond the scope of this contract, the more rigorous interaction loss analysis in conjunction with hardware design was made only for the selected propellant combination.

f. Mission and System Parameters

(1) Lunar Missions

The Lunar Descent and Ascent missions were based on respective ideal velocity increments of 7745 and 6882 ft/sec with propellant weights of 17,500 and 5000 lb. The propulsion system parameters that had to be determined in order to evaluate the performance of the gelled propellants were vehicle-thrust to weight fraction (F/W_{VEH}), nonvolume-dependent-weight to thrust fraction (W_{NVD}/F), and volume-dependent-weight to propellant-tank-volume ratio (W_{VD}/V_T).

For the Lunar Missions, the values of these propulsion system parameters were derived from modifications of the system designs of Reference 1. The thrust-to-weight fractions used for the Descent and Ascent Missions were similar, i.e., 0.38 and 0.40, respectively.

The remaining parameters were affected by two factors: a large weight allowance for inert components on the Descent Vehicle and the difference in the sizes of the propellant tanks between the two vehicles. The high inert weight on the Descent Vehicle raised the nonvolume-dependent-weight to thrust ratio to 0.32, in comparison to 0.082 for the Ascent Vehicle.

During previous propellant/mission performance studies by Aerojet-General, it was noted that for the same mission most propellants would have the same volume-dependent-weight to propellant-tank-volume ratio. The exceptions, LF_2/LH_2 and LO_2/LH_2, were caused by significantly different propellant bulk densities. For the LF_2/LH_2 system, the ratio (W_{VD}/V_T) was usually somewhat lower than most systems, with LO_2/LH_2 somewhat lower than the LF_2/LH_2 system.

All of the Lunar Mission and system parameters which were used in the propellant performance analysis are summarized in Table 7.

(2) Space Probe Mission

The Space Probe Mission requires 13,000 lb of propellant to deliver an ideal velocity increment of 7500 ft/sec after a 15-month storage in space. The propulsion system was considered to be a pressure-fed system with an ablative chamber delivering 8000-lb thrust. Each propellant was stored in two spherical propellant tanks.

The three system parameters required for the propellant performance analysis were determined by modifying a system designed for the Voyager retropropulsion maneuver (Reference 5). The thrust to vehicle-weight fraction was 0.29, and the nonvolume-dependent-weight to thrust fraction was 0.088, similar to the Ascent Vehicle. Basic tank weights are higher for the Space Probe Mission because of the long-duration mission with a high reliability requirement, coupled with fairly severe cost limitation. Thus, conservative design, rather an extensive testing to achieve the required reliability, was the approach used for this system. Insulation, when required, was assumed to be 210 layers (3 in. thick) of NRC-2 super insulation on 4-ft-dia spherical tanks (Reference 6).

The mission and system parameters for the Space Probe Mission are listed in Table 8.

Because of the 15-month space storage required for the Space Probe Mission, propellant storage conditions and possible boiloff or freezing of the propellants had to be estimated in evaluating their potential performance. Figures 3 and 4 (Reference 7) show that by regulating the projected surface area which is exposed to solar radiation and by controlling the absorbtivity-to-emissivity ratio of the propellant tank surface, a wide range of surface equilibrium temperatures may be obtained.

Based on the above equilibrium temperature calculations and shadow shield experiments by the NASA Lewis Research Center (Reference 8), it was assumed that OF_2 and possibly LF_2 could be space stored for 15 months without boiloff. Thus, only LH_2 was eliminated from consideration for the space probe mission.

Storage without boiloff was made a requirement for the gel systems to avoid changes in gelling agent concentration and to maintain known pressure drop characteristics. The conditions under which OF_2 could be space-stored without boiloff were investigated in more detail later in the program, Section III,B,3 of this volume.

An added comment on gelled propellant boiloff rates appears warranted due to the publication of apparently conflicting data. Reports have stated that gelling LN_2 reduces its boiloff rate to one-third that of neat LN_2 (Reference G18) and that gelling OF_2 did not materially alter the boiloff rate from that of neat OF_2 (Reference G19). The confusion arises from the tendency for the reader to assume that there is a one-to-one correlation between weight-loss-rate and volume-loss-rate for particulate (gelling agent) gels. Aerojet's tests with LN_2 and LO_2 gels have shown that the volume-loss-rate is significantly lower than weight-loss rate for particulate gels. This factor is believed to have caused the confusion in the interpretation of boiloff data for particulate gels.

g. Mission Performance Calculation

The mission performance calculation for each gelled and neat propellant combination was calculated using an Aerojet-General-developed computer program (Reference 9). The program uses the propellant densities; ullage, outage and boiloff allowances; and the mission and system parameters described in the previous section to calculate vehicle performance characteristics. Most of the performance characteristics are printed out per pound of payload for ease in scaling. The particular parameter which was used to rate the performance of the propellants was the payload-weight to vehicle-launch-weight fraction, the launch weight being calculated prior to propellant boiloff during storage. Therefore, each propellant was evaluated on the basis of delivered payload for identical launch weights.

h. Mission Performance Results

(1) Lunar Missions

The results of the mission performance calculations for the gelled and neat propellants for the Descent and Ascent Missions are shown in Figures 5 and 6. For both lunar missions, the best performing neat propellant combination was LF_2/LH_2 followed by LF_2/N_2H_4 Blend and LF_2/B_2H_6.

When the propellants are gelled, however, the LF_2/LH_2 system is more severely penalized than most of the other systems because of the relatively large amount of Li, 13.3 wt% (2 vol%), required for the low density LH_2. This extra metalizing of the propellant combination increases performance losses for the system because of (1) the thermal lag in transferring heat from the <u>just reacted</u> LiF particles to the gas stream (loss of usable heat for gas expansion), and (2) the increased kinetic loss caused by higher flame temperature. As a result, for the Descent Mission, the performances of the 96.5% LF_2 + 3.5 LiF/86.7% LH_2 + 13.3% Li and the 96.5% LF_2 + 3.5% LiF/98% N_2H_4 Blend + 2% CP* are comparable with only a 1.1% reduction in payload resulting from the use of the gelled LF_2/N_2H_4 Blend system rather than the gelled LF_2/LH_2 system. Because the Ascent Mission had a much smaller nonvolume-dependent-weight to thrust fraction, the performance of the gelled LF_2/LH_2 was penalized even further because of its low bulk density and the gelled LF_2/N_2H_4 Blend system out-performed it.

Because of the relatively short mission duration, no allowance was made for propellant storage losses.

*An Aerojet-General Corporation proprietary gelling agent.

By referring to Table 6, it can be seen that in every case in which a comparison was made the best mission performance occurred at the mixture ratio corresponding to the maximum delivered specific impulse, rather than when using the estimated delivered specific impulse at the theoretically optimum mixture ratio. The performance loss due to kinetics was always more significant than the increased bulk density at the higher mixture ratio, even with the LF_2/LH_2 systems.

(2) Space Probe

The results of the mission performance calculations for the Space Probe Mission are shown in Figure 7. The figure also indicates the number of propellants that were considered to require insulation since insulation affects the volume-dependent weight. On a no-boiloff comparison, gelled (LF_2/N_2H_4 Blend) outperforms the second and third best propellants gelled (LF_2/B_2H_6) and gelled (OF_2/B_6H_6), 28%; however, the no-boiloff, space-storability of 4000-lb of neat or gelled LF_2 for 15 months is rather questionable. If it proves that gelled LF_2 or gelled FLOX cannot be space-stored for 15 months without boiloff in this quantity, then the OF_2 systems will be the highest performing systems. The performance of a gelled LF_2/N_2H_4 blend system with 7.5% LF_2 boiloff was also calculated but rejected due to the necessity of avoiding boiloff in order to gel predict flow losses with any degree of accuracy.

While suitable space-storage conditions may be obtained for the propellants (shadow shields, reflectors and proper surface coatings), prelaunch conditions may require insulation. Therefore, the space probe system performance is also presented as a function of the number of propellants requiring insulations, Figure 8.

As can be seen from Figure 8, added insulation lowers system performance because it increased the volume-dependent-weight to tank-volume ratio; 7.9, 8.4, and 8.9 lb/ft^3, corresponding to no insulation, one propellant insulated, and both propellants insulated. Insulation weights (70 lb/propellant) were based on each propellant requiring two 4-ft-dia spherical tanks covered with 210 layers (3 in. thick) of NRC-2 super insulation (Reference 6).

For comparison with the high-energy propellants, the performance of neat N_2O_4/AeroZINE 50 was calculated for the Space Probe Mission, assuming no insulation was required (W_{VD}/V_T = 7.9 lb/ft^3). The payload weight to vehicle launch weight fraction was 0.369, so that gelled (LF_2/N_2H_4 Blend) system with no-boiloff represents a 16.7% increase; gelled (OF_2/B_2H_6), a 17.1% increase; and gelled (OF_2/MMH), a 12.5% increase, Figure 7.

(3) Selected Propellants

The gelled propellant combination selected for further study for all three missions was gelled OF_2/MMH (90.8% OF_2 + 9.2 ClF_5/ 99% MMH + 1% Colloid 8010). This combination was selected on the basis of the availability of flow data for the propellants. Considerably more work has been performed with gelled OF_2 than with the other two oxidizers, and the measurement of the flow properties for gelled OF_2 was scheduled under Contract NAS3-6286. FLOX has not been gelled, and LF_2 has been gelled only a couple of times to demonstrate feasibility. Also LF_2 space storability was questionable.

After determining that the oxidizer would be gelled OF_2, the fuel MMH was selected after conferring with the customer and examining a study which selected neat MMH as the best fuel for space system use with neat OF_2 (Reference 7). B_2H_6 has never been gelled; therefore, no data are available for it.

5. Gelled Propellant Modification Program

As previously discussed, the definition of the "ideal" value for a given propellant characteristic must be defined by specific mission requirements, and may, in fact, be different for different missions. However, the following areas of improvement are desirable in most applications for most gelled propellants.

In General:

(1) Reduce the amount of gelling agent.
(2) Make gels more cohesive to minimize tank hold-up.
(3) Further reduce evaporation rates.
(4) Increase yield stress while reducing high-shear viscosity.
(5) Improve mechanical and chemical stability.
(6) Prevent rheological property changes with time.

The obvious approach to changing gelled propellant properties is to change the gelling agent. The following are several suggested approaches:

(1) Find a new, more effective gelling agent.
(2) Chemically modify existing gelling agents.
(3) Use mixtures of gelling agents.
(4) Develop gellants with smaller particle sizes.
(5) Vary particle size distribution.
(6) Investigate other types of systems giving similar end-products, such as emulsions.

Two specific system improvements appear very desirable. If these propellants were re-evaluated as gels, better gelled propellant performance for the gelled OF_2, LF_2 and FLOX systems would be obtained using frozen particles of ClF_5 to gel the oxidizers rather than the inert LiF particles. The improved performance OF_2 gel (ClF_5 gelling agent) was used with MMH and exhibited the least performance loss in comparison to the corresponding neat propellant performance for the Lunar Descent Mission (Figure 5).

It is also likely that better gelled LF_2/LH_2 performance could be attained if frozen particles of CH_4 were substituted for Li particles in the LH_2 to reduce the reaction flame temperature and corresponding kinetics losses as well as eliminate two phase flow losses by avoiding LiF particles in the combustion products.

B. TASK II--PRELIMINARY ANALYSIS

1. Selected Propellant Properties

Properties were developed for the two propellants which have been selected for use in the remainder of this contract. The physical properties are listed in Table 9, and the flow curves are shown in Figures 9 and 10.

The properties of gelled OF_2 were estimated wherever possible from cryogenic gel data. This propellant has been designated GOF_2-E1, "G" for gelled and "E1" for estimate one. Most of the properties of GMMH-S1 ("S1" for simulant one) were taken from data for gelled MHF-3. Since MHF-3 is 86% MMH and 14% N_2H_4, it was assumed that the properties would be very similar for GMMH. The terms estimate and simulant are an indication of data confidence.

It was anticipated that simulant-two or estimate-two propellants might become necessary as the work developed. GOF_2-E2 (9.2% ClF_5 gelling agent) later replaced GOF_2-E1 (3.4% LiF) but the same basic physical properties were estimated so they can be used interchangeably with respect to density, freezing point, yield stress, flow properties, etc., except as noted in the following sections.

The following sections discuss the techniques used to arrive at the physical-property values:

a. Density

The densities were calculated from the measured densities of the neat propellants. It was assumed that the LiF was completely insoluble in the OF_2 and that the Colloid 8010 was completely soluble in the MMH. This has been demonstrated for the fuel and it has also been shown that other particulate gelling agents, such as SiO_2, are insoluble in both the fuels and oxidizers tested. Gelling slightly increases the density of the oxidizer, because a dense solid is added, and of the fuel, because weight is added with no change in volume.

b. Freezing and Boiling Points

Experience has shown that gelling has little or no effect on the freezing or boiling points of propellants. In any case, the boiling point is not the upper temperature limit of the gel. For Colloid 8010 this has been demonstrated (Ref D9) to be in excess of +165°F. For OF_2 the gel stability has been demonstrated up to the normal boiling point (-230°F) (Ref G19).

c. Critical Temperature

It was assumed that the critical temperature is unchanged by gelling.

d. Yield Stress

Most of the nonmetallized earth-storable gels have been shown to be stable at about 1000 dynes/cm^2. While most of the cryogenic systems tested had yield stresses of less than 500 dynes/cm^2, none were demonstrated to be storable for more than one month. Furthermore, since different types of instruments were used to measure the yield stress of the two systems, direct comparison may not be valid. To be on the conservative side, yield stress was set at 1000 dynes/cm^2 for both propellants.

e. High-Shear Viscosity

The high-shear viscosity measured on the Ferranti-Shirley Viscometer at 17,300 sec^{-1} is a convenient measurement which gives an indication of the shear-thinning nature of the gelled propellant. The values listed in Table 9 were estimated from available data on gelled N_2H_4, gelled MHF-3, and gelled, metalized MHF-3.

f. Bulk Modulus

The bulk modulus given for GMMH-S1 is the value measured for neat MMH. The value of GOF_2-E1 is estimated from values for liquid oxygen and liquid nitrogen. The adiabatic coefficients of compressibility are 0.7×10^{-5} in.^{2}/lb for LO_2 and is 1.1×10^{-5} in.^{2}/lb for LN_2. The isothermal value for LO_2 is 1.25×10^{-5} in.^{2}/lb. The average of these three values is about 1×10^{-5} in.^{2}/lb, and this has been used for gelled OF_2.

g. Heat Capacity and Heat of Vaporization

The heat capacities and the heats of vaporization of the gels were assumed to be the same as the measured values for the neat propellants. The one exception was the heat capacity of the gelled OF_2, which was corrected for the 3.5% solid LiF.

h. Propellant Flow Properties

Curves of shear rate versus shear stress for GOF_2-E1 or GOF_2-E2 and GMMH-S1 are shown in Figures 9 and 10, respectively, along with the flow properties for neat (not gelled) OF_2 and MMH for 1.76- and 0.884-in.-ID tubing.

The flow rheograms are log-log plots of shear stress $\frac{D\Delta P}{4L}$, versus shear rate, $\frac{8V}{D}$, for a straight tube with a circular cross section. In a given system configuration, with L and D fixed, the rheograms are a measure of pressure drop as a function of flow rate. Since the density of the neat propellant is usually quite close to that of the gel, equal flow rates represent equal shear rates, so that pressure drops in gels and neat fluids can be easily compared on the rheograms. Pressure-drop comparisons are discussed in a following section.

In the laminar region (single lower slope line), the instantaneous apparent viscosity of the gel is the ratio of shear stress to shear rate, lb-sec/in.^{2} This apparent laminar viscosity is used in calculating the Reynolds number of the gel.

Since there are no rheological data for gelled OF_2, considerable interpolation and estimation were required. The slope of the laminar line was chosen by interpolation between gelled LH_2 and another gelled propellant. The laminar-to-turbulent flow transition point was assumed to occur at a Reynolds number of 2000 using the instantaneous apparent viscosity. The validity of using the usual Reynolds numbers for non-Newtonian gels has not been established theoretically, however. One theoretical analysis indicates that a slope of 7/4 or 1.75 is expected for turbulent flow and this slope was used as turbulent gel flow data has correlated reasonably well with it. Data on which the flow properties were selected are discussed in Volume 2, Section III,B,1 of this report.

The GMMH-S1 flow curve in Figure 10 was taken directly from room-temperature flow data for MHF-3 gelled with 1% Colloid 8010. The only high- and low-temperature flow data available for MHF-3 were from gel using an Aerojet-proprietary gelling agent (C.P.). For this gel, the flow-curve values increased to approximately double at -20°F and decreased to approximately 1/2 at +165°F. These factors were used to plot the high- and low-temperature curves in Figure 10.

2. Comparative Pressure Drops

Pressure drops for the gelled and the neat (nongelled) propellants were compared. First the pressure drops were compared for flow in straight tubes and orifices. Then, with allowances for the different flow properties, pressure drops were estimated for a typical gelled and a typical neat propellant in pressure-fed propulsion systems.

a. Straight Tubes

Comparisons between the pressure-drop, $\frac{D\Delta P}{4L}$, and flow-rate, $\frac{8V}{D}$, relationships for the selected propellants in the gelled and neat conditions are shown in Figures 9 and 10. The curves are for straight circular tubing.

(1) Neat Propellant

In each figure, the pressure drop for the neat propellants were calculated for the 1.76- and 0.884-in.-ID tubing using Darcy's equation for pressure drop with values of Darcy's friction factor and relative surface roughness taken from Crane Company's Technical Report No. 410.

The slopes of the neat-propellant turbulent lines range between 1.84 to 1.94, since the flows are not fully turbulent. Even though the Reynolds numbers for the neat propellants ranged from 10^4 to 10^7 (for shear rates between 10^3 and 10^4 sec^{-1}), the low relative roughness for the drawn tubing resulted in varying friction factors. To obtain fully turbulent flow, the Reynolds number must be high enough to enter the region on a Moody diagram in which the friction factor no longer varies with increasing Reynolds number. The slope of the turbulent line increases to 2.0 as it enters this region and remains constant in it.

(2) Gelled Propellant

The rheograms indicate that for the same tube size the pressure drops of the gel may be greater than those of the neat propellant by a factor of as much as 2.0 to 2.4 in the turbulent regime and by a larger factor in the laminar regime; therefore, larger tube diameters are selected for the gels than for the neat propellants. Even with this large difference in pressure drops for equivalent flow, moderate increases in line size are sufficient to bring the gel line pressure drops of the gel back down to the values typically used for neat propellants.

For instance, the range of gelled-propellant flow rates which are currently being used for the injector-design effort are from to 2 to 12 lb/sec for GMMH-S1 and 5 to 26 lb/sec for GOF_2-E1 or -E2. By inspecting the tabulated flow data for the gel laminar-turbulent transition points shown in Figures 9 and 10, it can be shown that the highest flow rate can be handled by 2-in. tubing (1.76-in. ID). For GMMH-S1 at -20°F, the pressure drop in the high laminar region would be 0.64 psi/ft while for GOF_2-E1 the pressure drop would be 0.49 psi/ft in the low turbulent regime.

A firm weight trade-off between increased pressure drop and increased line and valve size for gelled propellants can not be made until actual gel properties can be applied to some specific systems.

(3) Effects of Gel Properties

It should be noted that the selected gelled propellant flow characteristics can be regarded as only representative trends for gelled propellants rather than as definite characteristics of specific propellants. For example, the selection of a Reynolds number of 2000 for a sharp transition point from laminar to turbulent flow was somewhat arbitrary, since gel flow data have shown a fairly wide range of transition Reynolds numbers.

The relative pressure drop at the laminar-turbulent transition point for GMMH-S1 and neat MMH at the same flow rate is affected by the Reynolds number at which the sharp transition is assumed to occur. The dependency on Reynolds number is illustrated in Figure 11 for the fuels at 77°F in a 1.76-in.-ID tube. Relative gel-neat pressure drops for all points in the low-turbulent gel region will be similarly affected by the selection of the transition Reynolds number.

It is expected that the transition between laminar and turbulent flow will not be as sharp as assumed in the flow properties for GOF_2-E1 and GMMH-S1. Test data indicate that the sharp corner of point transition should be rounded, but, because of data scatter in the transition region, the idealized point transition is considered adequate until the transition region is better defined. Also, while the slope of the turbulent line appears to be about 1.75 as it emerges from the transition, the slope of the turbulent gel line is expected to increase at higher shear rates until it approaches the local slope of the neat-propellant line (1.8 to 2.0). If this were not the case, the gel turbulent line, with its lower slope, would cross the neat-propellant turbulent line at some higher flow rate and the gelled propellant would then have a lower pressure drop than the neat propellant. It is considered unlikely that such a cross-over occurs; rather it is expected that the two turbulent lines will approach asymptotically and that no difference between gel and neat fluid pressure drops will be observed when the gel flow is also highly turbulent. However, the shear rates required to reach the highly turbulent gel region would probably result in propellant line pressure drops which are above reasonable design limits. Therefore, gelled propellants will usually require somewhat larger lines than the corresponding neat fluid.

b. Orifices and Injectors

Considerable variation in injector orifice pressure drops has been reported in comparing gelled and neat (non-gelled) propellants at the same flow rates. Data has ranged from "no change" in pressure drop to increases of about 40% and, in one case, a decrease of 46%. This data is discussed in Volume 2, Section III,B,2 of this report.

The "no change" or higher pressure drops are believed to be more typical gel property, but propellant flow data should be obtained before committing hardware to fabrication unless orifice adjustments can be made easily.

It is believed that the viscous effects of both the gel and neat fluid become negligible at high shear rates, so that for the same pressure drop the flow velocities will be equal. If the vena contractas of the orifice are equal for the two fluids, then the gel flow rate can be predicted from the neat-fluid data.

The lower than Newtonian pressure drop is explained by a condition where a stagnant layer of gel accumulated on the tube wall and the orifice plate to create the effect of a smooth transition rather than the sharp discontinuity experienced by the Newtonian fluid. Thus, the high viscosity of the gel in the less turbulent region approaching the orifice may have a significant effect on the gel flow rate.

A corollary of the above hypothesis is that gelling a fluid should not affect its high-shear flow properties through a venturi (an orifice with a smooth approach). A comparison between water and a gel with an organic gelling agent showed equivalent flow coefficients for the gelled and neat fluids.

As indicated above, when the pressure drop through an orifice is reduced, the flow rates of the gelled and neat fluids which were both Newtonian turbulent, begin to diverge as the viscous losses of the gel affect the flow long before the low viscosity of the Newtonian fluid becomes significant. Thus, in the low turbulent and laminar region the pressure drop comparison between the gelled and neat propellants should diverge in a manner similar to that predicted for straight tubes in these same shear rate regions.

The low turbulent and laminar flow characteristics of gels will be most significant in throttlable injector design. In the low turbulent region if a gel has a pressure-drop flow-rate exponent of 1.75, then throttling 10:1 only reduces the injector pressure drop by 53:1 rather than by 100:1 as with a fully turbulent Newtonian flow (exponent of 2.0). The striking difference in gel flow properties is in the laminar region where the flow-rate pressure-drop exponent for 77°F GMMH-S1 is 0.434. For an order of magnitude reduction in flow rate (shear rate), the injector pressure drop would only be reduced by 2.7:1 (shear stress).

The reduced variation in injector pressure drop with flow rate will improve low frequency combustion stability at the throttled condition but obtaining good gel atomization for the reduced flows in conventional injectors will continue to be a design problem which may be aggravated by gelling the propellants. The HIPERTHIN platelet design may eliminate the atomization problem while taking full advantage of the gel's laminar throttling pressure drop characteristics.

c. Pressure-Fed System

A comparison was made between the system pressures for a typical pressure-fed spacecraft propulsion system and the same system using gelled, nonmetalized propellants. The gelled propellant pressure drops selected are believed to be conservative and represent an upper limit for the gelled propellant in comparison with the corresponding neat propellant.

Based on a chamber pressure of 100 psia for each system, the propellant tank pressure was 210 psia for the neat propellants and 275 psia for the gelled propellant system; an increase of 31%. A breakdown of the pressure and pressure drops used is listed below.

	Neat	Gelled
Tank pressure, psia	210	275
ΔP, line and valve, psia	50	75
Injector inlet, psia	160	200
ΔP, injector, psia	60	100
Chamber pressure, psia	100	100

The line and valve pressure drop was increased by 50% for the gelled system because of unknowns in valve pressure drop characteristics for the gelled system.

The injector pressure drop was increased 67% to account for increased pressure drop for the same flow rate plus an increase in velocity to ensure adequate gel breakup upon impingement.

3. Heat-Transfer Effects

a. Regenerative Cooling Capabilities of Gelled Properties

In the latter part of the 1950s success was first reported in preparing a metalized gel propellant for improvement in rocket engine performance, and interest was noted in gelled storable propellants because of their improved safety aspects. From that time to the present, considerable effort has been expended in the development of gels for rocket engine propulsion. However, there has been no appreciable work to determine their value as a coolant in regeneratively cooled rocket engines.

Five specific types of information are required to adequately describe the regenerative cooling capabilities of a propellant. These are:

1. A heat-transfer coefficient correlation for wall temperatures lower than the saturation or decomposition temperature of the propellant.

2. For subcritical pressures, a correlation defining the heat flux--wall temperature relationship when nucleate boiling occurs.

3. The maximum allowable heat flux which can be transferred to the propellant without experiencing coolant tube burnout, i.e., the ultimate heat-flux limit.

4. The detonation limit of the coolant, i.e., the coolant bulk temperature above which detonation will occur.

5. A relationship for calculating pressure drop.

Heat transfer coefficient data are available for many non-Newtonian fluids, although the bulk of the data is for nonpropellants such as water and corn syrup gelled with Carbopol and water, Attagel slurries. These data have been correlated by Metzner and by Clapp (Refs 10 and 11). In a literature survey made for this report, the only gelled propellant heat-transfer data found was that taken at Aerojet-General Corporation during the course of ultimate heat flux tests of Alumizine, a hydrazine gel loaded with aluminum particles. While these data tended to indicate that metalized gelled propellants are relatively poor coolants having nonrepeatable characteristics, it is felt that these data are not necessarily characteristic of all gels because of the large amount of aluminum in the propellant. Obviously, much more data for a variety of propellants are required before it can be determined if the correlations for nonpropellants are applicable to propellants, or before a correlation for propellants can be developed. However, the correlations for nonpropellants can be used as first approximations in any analysis performed prior to obtaining test data. The preceding remarks are also applicable to pressure drop calculations.

No information is available with respect to heat transfer with gelled propellants when they experience local boiling or decomposition during forced flow. Here again, the only data available are those mentioned above for Alumizine, and it is difficult to draw any meaningful conclusions from these data.

Some gels break down at elevated temperatures. Proper selection of the gelling agent may allow thermal destruction of the gel structure upon entering the cooling section and produce Newtonian flow for cooling and injector flow following storage as a gel.

In summary, little is really known about the cooling capabilities of gelled propellants, and experimentation is needed to develop an understanding of this area. The required testing is similar to that which has been and is now under way to obtain heat-transfer data for nongelled propellants. Basically, this involves flowing the propellants through electrically heated tubes while measuring tube temperatures, power dissipation in the tube, and propellant bulk temperature rise. This method can supply precisely the data required for the five categories of information mentioned above.

Operational problems may be encountered in using gelled propellants for regenerative cooling. Since the work history of certain gels affects their pressure drops, the calculation of regenerative system pressure drops can be complicated by this added variable. The gelling agent residue in a regenerative tube-bundle might prove to be difficult to clean and remove should evaporation be allowed to occur.

b. Propellant Storage

Some of the aspects of heat transfer in long-duration simulated space storage of cryogenic and noncryogenic gelled and nongelled propellants have been studied. The investigation does not account for the nature of the vehicle onto which the propellant storage tank is mounted, and considers the tank to have radiant energy exchange only between the sun and space. The parameters used for the study were:

1. The propellants are gelled and neat MMH, and gelled and neat OF_2.

2. The tank is a 4-ft-dia sphere.

3. Solar irradiation is 442 Btu/ft^2-hr, corresponding to the outer fringes of the earth's atmosphere.

4. Acceleration forces acting on the propellant are a solar force of 5×10^{-7} g_o plus an attitude-control-system force of 5×10^{-6} g_o acting in the same direction as the solar force.

5. The propellants are at thermal steady-state.

For the tank wall, it has been assumed that there is no temperature gradient in the radial direction and no heat conduction in the azimuthal direction.

A description of the study performed for each propellant and a discussion of the results follows. A list of symbols used in the analyses is presented as Table 2.

(1) Neat MMH

The investigation for nongelled MMH was made to determine what difficulties might be encountered to prevent propellant boiling on the side of the storage tank that faces the sun and freezing on the opposite side. For storage at a pressure of 1 atm, this condition limits the tank to a temperature range of -60 to 190°F.

With regard to the heat-transfer analysis used for this determination there are two major uncertainties.

1. Is the mechanism of heat transfer between the tank wall and the propellant, primarily convection or, because of the low gravity field, conduction?

2. If the mechanism is convection, to what degree will the propellant stratify?

The criteria used to ascertain the mechanism were the product of Grashof number and Prandtl number (GR·PR). For values of this product between 10^4 and 10^9, McAdams (Ref 12) recommends the use of a laminar flow, natural convection coefficient for heat transfer from a vertical plate. A similar coefficient is recommended for a horizontal heated plate facing upward (somewhat similar to the sun side of the tank) if the product ranges from 10^5 to 2×10^7. Since there is a lack of data for natural convection within spheres, these data for plates were used as the criteria. To determine the order of magnitude of (GR·PR), the product was calculated for a MMH film temperature of 0°F and a dimension of 1 ft. The calculation showed that for temperature differences from the tank wall to the MMH bulk of 25°F or greater the product (GR·PR) was larger than 10^5. Therefore a convective heat-transfer mechanism was used. As anticipated, it was subsequently found that the temperature difference was greater than 25°F over the major portion of the tank, and the use of natural convection was justified.

An attempt to determine the degree of stratification within the tank was beyond the scope of this investigation. Therefore it was assumed that stratification does not take place and the propellant bulk is at a common temperature.

Because the amount of work done to establish a natural convection heat-transfer coefficient correlation for a fluid contained in a sphere is limited, use was made of flat-plate correlations to estimate the heat-transfer coefficient. The recommended correlation for a vertical plate is:

$$Nu_f = 0.59 \; (GR_f \cdot PR_f)^{0.25} \qquad \text{(Ref 12)} \qquad \text{(Eq 1)}$$

It differs from that for a heated plate facing upward

$$Nu_f = 0.54 \quad (GR_f \cdot PR_f)^{0.25} \qquad \text{(Ref 12)} \qquad \text{(Eq 2)}$$

only in the coefficient (see Table 10 for symbol list). Considering the similarity of these correlations and the lack of work done for spheres, Eq 1 was used as a first approximation for the convective heat-transfer coefficient calculations. It is probably a fair approximation since, subsequent to the analysis, it was found that Schmidt (Ref 13) recommends the use of the following correlation:

$$Nu_f = 0.65 \quad (GR_f \cdot PR_f)^{0.25} \qquad \text{(Ref 13)} \qquad \text{(Eq 3)}$$

in which the significant dimension is tank diameter. If Eq 3 is an accurate correlation, the calculated coefficients may be in error by 20% since the dimension used in the calculations was 1-ft dia instead of 4-ft dia. It was felt that reanalysis was not justified in view of the uncertainty with respect to stratification.

The thermal model used for this analysis is shown in Figure 12. Steady-state temperatures were calculated by the Aerojet Thermal Network Analyzer computer program which solves n-dimensional heat flow problems through the use of an electrical analog of the thermal network. Finite difference methods are employed.

The results of the analysis are shown in Figure 13 for tank surface conditions of

$$\frac{\alpha_s}{\varepsilon} = 1.0$$

$$\varepsilon = 1.0$$

As can be seen from the figures, tank temperatures range from 2°F to 130°F with the bulk temperature at 40°F. For the conditions of the analysis, neither boiling nor freezing of the propellant will occur. The indication is that no extreme difficulties would be encountered in the design of storage tanks for the neat MMH.

(2) Gelled MMH

The purpose of this study is identical to that for the neat MMH, i.e., the determination of the precautions which must be taken to avoid propellant boiling or freezing. Again, the tank pressure was taken at 1 atm, limiting the propellant temperatures to the range -60 to 190°F.

The analysis for the gelled MMH is less questionable and somewhat more straightforward than for the neat, because the mechanism of heat transfer through the propellant is definitely conduction. Figure 14 depicts this thermal model used for the analysis. The Thermal Network Analyzer was again used to calculate steady-state temperatures.

Two cases were analyzed, and the results are shown in Figures 15 and 16. In the first case, the tank surface conditions were the same as those used in the neat MMH analysis.

$$\frac{\alpha_s}{\varepsilon} = 1.0$$

$$\varepsilon = 1.0$$

Propellant temperatures range from -250°F to 250°F. These temperatures indicate that tank surface conditioning or shielding is required to reduce the temperature spread and maintain the propellant temperature higher than the freezing point on one side of the propellant bulk and lower than the boiling point on the other side.

Using the results of the first case as a basis for estimating the required surface conditioning, the second case was analyzed for

$\alpha_s = 0.5$

$\varepsilon = 1.0$ (emissivity on sun side)

$\varepsilon' = 0.02$ (emissivity on opposite side)

For these tank surfaces, the propellant temperature spread, with the exception of a section of tank from $75° < \theta < 90°$, is from -40°F to 135°F--acceptable from the point of view of freezing or boiling. Although the analysis was done for solar absorptivity of 0.5 and a sun side emissivity of 1.0, the results of the analysis would not change significantly if their absolute values were changed somewhat but the ratio of absorptivity to emissivity was maintained at 0.5. The reason for this is that the tank surface is almost an adiabatic wall, i.e., the heat conducted into the propellant is approximately two orders of magnitude less than the solar heat absorbed or the heat radiated from the surface. For a true adiabatic wall, the tank surface temperature would be purely a function of the ratio of absorptivity to emissivity.

The low temperature, -78°F, shown on the section of tank at $75° < \theta < 90°$ is due to the shallow angle of incidence of the sun's radiation on this surface. To bring this temperature up above -30°F, the surface in this area would have to be conditioned to have a higher value of the ratio of solar absorptivity to emissivity, approximately 1.

Although the tank surface conditioning in the second case would eliminate boiling or freezing, it has two drawbacks. The first is the strong probability of degrading the highly reflective ($\varepsilon' = 0.02$) "shade" side surface of the tank during long storage times in space because of exposure to stray ultraviolet radiation or because of bombardment by micrometeorites. The second drawback is the nonisothermal condition of the propellant. Since the rheological properties of gelled MMH change significantly over the temperature range of -40°F to 135°F, the flow rate would change significantly during an engine firing with a fixed tank pressure.

In view of these disadvantages it would be recommended that for gelled MMH storage, radiation shielding be used to maintain the propellant temperature extremes within narrower limits.

(3) Neat OF_2

Since OF_2 is a cryogenic with a saturation temperature of -230°F at 1 atm--the assumed tank storage pressure--the main concern in this section of the investigation was to find how the boil-off rate of the OF_2 could be kept to an acceptable level or eliminated completely. The problems associated with this analysis are similar to those for the neat MMH analysis; the mechanism of heat transfer at the tank wall and the degree of propellant stratification are questionable. As with the neat MMH, it has been assumed that stratification does not take place, i.e., the propellant bulk is isothermal.

For situations in which OF_2 boiling takes place, i.e., there is a net heat flux into the tank, the heat transfer mechanism at the sun side of the tank is nucleate boiling. Rohsenow (Ref 14) states that the maximum heat flux in nucleate boiling can be calculated as follows:

$$\frac{(q/A)\ max}{\rho_v\ h_{fg}} = 143 \left(\frac{g}{g_o} \right)^{1/4} \left[\frac{\rho_L - \rho_v}{\rho_v} \right]^{0.6} \text{ft/hr} \quad \text{(Ref 14)} \qquad \text{(Eq 4)}$$

For OF_2, this heat flux is 0.0274 Btu/in.^{2} sec. Since solar radiation to a black body is 0.000852 Btu/in.^{2} sec, and it is the maximum possible heat flux to the tank wall, the OF_2 will experience nucleate boiling and not film boiling. Nucleate boiling implies a small temperature difference between the tank wall and the propellant bulk, so the sun-side tank wall has been taken to be the saturation temperature in this case.

Convective heat transfer coefficients have not been calculated for the "shade" side of the tank. Because of the lack of data with respect to the coefficient of expansion of subcooled OF_2 needed to calculate the Grashof Number, in addition to the uncertainties of stratification and convective heat transfer within a sphere, it is felt the calculation would not be warranted. Since the analyses were done for propellant boiling or, in the limit, prevention of boiling, the OF_2 bulk temperature was taken to be the saturation temperature. The shade side of the tank was therefore also assumed to be at OF_2 saturation temperature. This may be a fair estimate because of the low heat flux radiated from the shade side of the tank at this temperature--9.25×10^{-6} Btu/in.^{2} sec.

For the above-stated conditions, a relation between boil-off rate and the solar absorptivity on the sun side of the tank is shown in Figure 17. If an acceptable boil-off rate is taken to be 2.21×10^{-5} lb/sec, a rate which corresponds to 10% boil-off in a 15-month mission, it can be seen that the solar absorptivity would have to be impractically small. In view of this, it was concluded that radiation shielding would be required to limit or prevent boil-off.

Figure 18 shows the thermal model used to determine the shielding required to prevent boil-off. The analysis was performed by finding the number of shielding elements which would limit the heat input to the sun side of the tank to a value equal to that radiated from the shade side, a net heat input of zero. As indicated in Figure 18, a shielding element is a thin sheet oriented parallel to the tank surface, and ideally having no thermal contact with the tank surface. The equation used in this study is as follows:

$$q = \frac{\sigma \times 10^{12}}{n\left[\frac{2}{\varepsilon} - 1\right]} \; 2\pi R^2 \left[\left(\frac{8.52 \times 10^{-4}}{\sigma \times 10^{12}}\right)\left(\frac{\alpha_s}{\varepsilon_1}\right)\left(\frac{\pi}{4}\right) - \left(\frac{T_{SAT}}{1000}\right)^4\right] \qquad \text{(Eq 5)}$$

In the development of this equation, it was assumed that the surface of the outboard shield element can be considered an adiabatic surface relative to solar radiation. From the results of the analysis (Figure 19), it is concluded that the neat OF_2 tank could be shielded to prevent boil-off.

(4) Gelled OF_2

The study was made to determine if "boiling" of the gelled OF_2 can be prevented without resorting to extreme measures in tank design. The thermal model used for the study was similar to that used for gelled MMH, with one exception. Because the limiting temperature on the sun side of the tank was the saturation temperature of OF_2 at 1 atm in order to prevent boiling, the temperatures on this side of the tank were held at -230°F.

With this condition, propellant temperatures were determined at steady state, along with heat rejected to space from the shade side of the tank. Propellant temperatures are shown in Figure 20.

Having determined the heat rejected to space, it was evident from the work done for the neat MMH that surfacing conditioning alone was not a practical method of preventing boiling. Therefore, the degree of shielding required was determined in the same manner as for the neat OF_2. The results of this analysis show that more effective shielding is required for the gelled than for the neat OF_2. Less heat is rejected to space since the shade-side temperatures are lower for gelled OF_2, requiring, therefore, that the heat input on the sun side be less.

It should be pointed out that if uniform shielding on the sun side of the tank is used, the condition of an isothermal surface on this side of the tank is only an approximation. There will be a variation in temperature as there is a variation in solar heating in the azimuthal direction. The result would be to lower the heat rejection to space and cause the results of this analysis to be somewhat unconservative.

It is concluded that radiation shielding can be used to prevent boiling in gelled OF_2 (Figure 21).

(5) Conclusions

As is evident from the preceding discussions, the work done in this study is idealized, and is presented to point out heat-transfer problems which will be encountered if one or any of the propellants are stored in space for a considerable length of time. It is not meant to be a detailed design study. Obviously more serious consideration would have to be given to the questions of propellant stratification and convective heat transfer coefficients for spheres in low gravity fields. The design of an actual heat shield, taking account of "heat leaks" between elements and end effects, would require study. The vehicle configuration could not be ignored in a real design study.

From this investigation, it can be concluded that any of the propellants studied can be stored in space--some with more difficulty than others.

4. Hydraulic Transients

The use of gelled propellants in liquid rocket engine systems has several advantages. From a hydraulic-flow point of view the main distinguishing feature of such propellants is their characteristic non-Newtonian flow. It was the purpose of this investigation to analytically evaluate the effect of these characteristics on engine transient performance.

a. Existing Liquid Engine Transient Model

Startup and shutdown transient simulation for Aerojet-General Corporation liquid rocket engines is usually obtained from the 109 computer program. This program uses a "building block" approach to simulate any engine by combining up to 100 components. Each component represents a line section, valve, thrust chamber, or similar item of the actual engine. The equations for each of these types of components are available in subroutine which are used as often as required. The effects of non-Newtonian fluids appear in calculating pressure drop versus flow rate. This was done in four commonly used subroutines: (1) SR-1--rigid line, (2) SR-2--elastic line, (3) SR-8--valve, and (4) SR-37--injector. In all these subroutines the existing program computes pressure drop (or solves for weight flow) from the basic equation:

$$\Delta P = C \frac{\dot{w}^2}{\rho}$$

where hydraulic resistance, C, is considered to be a constant.

b. Non-Newtonian Flow--SR16AB

A Newtonian fluid is one for which the ratio of shear stress to shear rate is constant (viscosity). In a non-Newtonian fluid the ratio of shear stress to shear rate is not constant, but is a function of shear rate and, in some cases, of the past history of the material. Thus, viscosity is no longer a useful concept, and it is necessary to use the shear stress versus shear rate diagram (often called a rheogram) to compute the pressure drop. Because of the use of pressure-drop calculations in several subroutines, and to increase flexibility, it was decided that instead of modifying each 109 subroutine, a new subroutine would be written which would calculate an effective hydraulic resistance as a function of flow rate and line size and then store the result in the existing component. This subroutine is numbered 16AB in the 109 system, and its flow chart is shown as Figure 22. Each entry into SR16AB permits the calculation and storage of up to six resistances. Certain features should be noted.

1. Each resistance can be split into two parts: one constant, and a second, a function of friction factor (shear stress). Thus, pressure drops can be represented as partly due to a straight velocity squared loss and partly to friction.

2. To use the existing valve subroutine the maximum diameter and wide-open resistance are inputed. An effective diameter is then calculated from the ratio of valve reference resistance (wide open) to the instantaneous resistance (obtained from a curve of K_w versus position), the ratio being taken to the one-fourth power.

3. Provision is included for computing an effective resistance for elastic (water hammer) lines where inlet and exit flow rates are different.

c. Assumed Engine

Once SR16AB had been checked out, it was used in obtaining typical startup, shutdown, and throttling transients for a pressure-fed liquid rocket engine. For convenience, an existing engine was selected and used with no changes except in propellants and pressure schedule. The engine selected was basically the current Apollo service module engine. The thrust chamber valve actuation system of the model was not used; instead, the valves were assumed to be actuated linearly by an external power source. All other hardware remained the same.

d. Propellant Properties and Pressure Schedule

The existing Apollo line sizes, injector, valves, and thrust chamber were used. Resistances were apportioned in the following manner:

A Reynolds number and a friction factor were computed for the current Apollo lines. These were used to compute a resistance for the line segment. This resistance was, in all cases, less than the resistance currently in the program. The difference was split--half as a velocity-squared loss, and half as an additional friction loss. Injectors, valve, and orifice resistances were similarly split with half of the current resistance assumed to be proportional to friction factor.

Chamber pressure was selected to produce 20,000 lb thrust. For the first startup case, tank pressures of 175 psia were used and the lines were orificed to obtain the desired operating point. As discussed in Section e, below, this resulted in the engine with gelled propellants starting faster than the engine with neat propellants. To provide a better comparison, it was decided that all remaining cases would use the same orificing for both engines and to change tank pressure to obtain the desired balance point. Steady-state pressure schedules for the gelled and neat propellants (Systems 3 and 4) are shown in Table 11.

Two sets of runs were made with the gelled propellants. The first set, Systems 1 and 2, used an erroneously low turbulent-slope for the gels while the second set, Systems 3 and 4, used the GOF_2-E1 and GMMH-S1 slope of 1.75. The erroneous turbulent slopes for the gelled oxidizer and fuel were only 1.06 and 1.34, respectively. At higher shear rates, these gels had lower pressure drops than the neat propellants. One example run with the erroneous gel data is included in the tabular data only to show how little the "gel" start transient was affected.

e. Start Transients

Start transients for the Systems 3 and 4 are shown in Figures 23 through 26. In all the plots the first part shows pressures, thrust, and valve position, whereas the second part shows weight flows and mixture ratio. Pertinent transient data are listed below:

System No.	1	2	3	4
Fuel	MMH	GMMH	MMH	GMMH-S1
Oxidizer	OF_2	GOF_2	OF_2	GOF_2-E1
P_{fT}, psia	175	175	134.8	148.4
P_{oT}, psia	175	175	124.3	154.3
Oxidizer fill time, sec	0.267	0.254	0.255	0.261
Ignition, sec	0.306	0.292	0.288	0.287
Time to 90% thrust, sec	0.369	0.340	0.323	0.329
Thrust overshoot, thrust, %	14.0	23.0	38.5	25.0

All transients were run with the same valve opening time of 500 millisec and the valve characteristics of the Apollo valves. The most noticeable feature of these transients is that the differences are relatively minor and of the type that can be modified by changing valve opening times or by modifying valve characteristics. Comparing Systems 1 and 2, it is seen that the engine using the gelled propellants with the low turbulent slope (System 2) started faster than the engine using neat propellants (System 1). This is primarily due to the different pressure drops during the fill period and the different orifices. The engine with gelled properties has a lower orifice drop because of higher pressure drops in the remainder of the system at steady state. During the fill period the orifice is primarily controlling the flow, and hence, the engine using the gels fills its manifolds quicker.

The remaining cases (Figures 23, 24, 25, and 26) were all run with the same orifice resistances and tank pressures adjusted to give the desired steady-state operating points, Systems 3 and 4. It will be seen that the gelled System 4 (Figures 25 and 26) shows a slightly lower startup than with the neat propellants. Again, this difference can be modified by changes in valve timing. Both cases show a considerable thrust overshoot due to the low system-resistances controlling at the time of ignition. Such overshoots can be reduced by opening the valves more slowly, by recontouring valve pintles, or by reducing manifold volumes.

f. Shutdown Transients

Shutdown transients for Systems 3 and 4 are shown in Figures 27, 28, 29, and 30. Differences in shutdown times, thrust decay curves, and first water hammer pressure spikes are completely negligible. Differences in the valve inlet pressures after valve closure will not normally be important but may be significant for a pulsed engine or for a system using multiple thrust chambers fed from a common manifold. The relatively low frequency (17 and 13 cps) shown in Figure 27 results because of the use of bellows in the Apollo lines. The rate of damping shown in Figure 27 for these oscillations is typical of the computer prediction; actual shutdowns generally show a higher damping rate. Figure 29 shows that the damping of these low-frequency oscillations is considerably increased with the gels. However, Figure 29 indicates the presence of a higher frequency oscillation not observed with the neat propellants. Cases run during program checkout have shown this type of oscillation to be characteristic of rheology diagrams having relatively flat slopes for the laminar line. It is believed that this oscillation will not be observed with real gels but is due to the lumped resistance character of the model.

g. Throttling Transients

Figures 31 through 34 show some typical throttling transients for Systems 3 and 4 in which thrust is reduced to approximately 25 to 30% of full thrust, with a valve closure time of 75 millisec. The valves used are not particularly suitable for throttling because they produced a large mixture ratio shift in the throttled condition. The cases are comparable, however, and illustrate that there are no significant differences in transient times between gelled and ungelled propellants for this type of throttling.

As indicated previously, the main difference between gel and Newtonian flow is encountered in throttling when the gel flow becomes laminar. The calculated flow rates and pressure drops for the neat and gelled oxidizers were substituted into the equation:

$$\left(\frac{\dot{w}_2}{\dot{w}_1}\right)^n = \left(\frac{\Delta P_2}{\Delta P_1}\right)$$

where:

$\dot{w}$ = flow rate, lb/sec

and ΔP = pressure drop, psi

The equation was solved for the controlling exponent "n" for the pressure drop from the oxidizer tank to the thrust chamber valve inlet and for the pressure drop across the injector with the following results:

	Neat OF_2	GOF_2-E1 or -E2
Flow rate ratio	2.11	2.30
n, tank to valve	1.68	0.745
n, across injector	1.99	1.90

Since values of n of 1.0 and 2.0 represent Newtonian laminar and turbulent flow, respectively, it can be seen that the gel flow became "gel laminar" ($n < 1.0$) during the throttling. The throttling was not deep enough to cause the injector gel flow to drop significantly into the laminar regime, although the gel flow across the injector is less turbulent than the neat OF_2 during the throttling.

C. TASK III--COMPONENT DESIGN ANALYSIS

1. Propellant Expulsion and Control

a. Positive Expulsion

Examination of available gel data and the operating characteristics of positive expulsion devices indicate that there should be no significant difference between using a positive expulsion device on a neat propellant and on a gelled propellant. Of course the gelled system may have a higher operating pressure due to higher pressure drops downstream of the expulsion vessel, but the operation of the positive-expulsion device and its expulsion efficiency would not be effected. Positive-expulsion devices considered were various metal diaphragms (bonded rolling, Arde' reversing hemispheres, the JPL corrugated expanding hemisphere, etc.) metal bellows, and nonmetallic bladders.

Gelled propellants will add their slosh and vibration damping effects to that of the positive-expulsion devices. The reduction in vibration and slosh due to the gel will be most pronounced with those devices which hold the propellant least rigidly. For nonmetallic bladders of Teflon or some elastomer, the primary benefit of a gel would be to somewhat reduce sloshing of the bladder-contained propellant bulk. For a metal bellows in a containment can, the primary benefit of gelling the propellant would be reduced vibration between the bellows and the pressure vessel. This would increase the usable life of the bellows by reducing vibration-induced fatigue at the bellows-leaf weld lines.

b. Gel Position During Weightlessness

Calculations indicate that the yield stress of the gel will maintain the position of the gel in the bottom of a propellant tank during weightlessness. Surface tension forces will not make it wet the walls of the propellant tank. A yield stress of 1000 dyne/cm^2 (0.0145 psi) is sufficient to overcome surface tension forces for a cylindrical section of tankage or tubing down to less than 0.060 in. dia.

This conclusion was reached by balancing the surface tension force against the yield stress force and solving for the diameter:

$$\pi D \sigma = \frac{\pi}{4} D^2 \tau_Y$$

$$D = \frac{4\sigma}{\tau_y}$$

where

d = diameter, ft

σ = surface tension, lb/ft

τ = yield stress, lb/ft

For example, N_2O_4 and AeroZINE 50 which have maximum surface tensions of about 33 dyne/cm (2.3×10^{-3} lb/ft) cannot overcome the 1000 dyne/cm^2 yield stress until the diameter of the cylinder is reduced to less than 0.052 in. The surface tensions of some cryogenic propellants are listed below for comparison. They are all much lower than the maximum values for the storables.

Propellant	Surface Tension (lb/ft)
LH_2	0.20×10^{-3}
LO_2	0.91×10^{-3}
LF_2	0.90×10^{-3}

c. Suitable Expulsion Devices

It appears likely that positive-expulsion devices will not be necessary for pressure-fed spacecraft propulsion systems which expell gels only while the main engine provides a helpful acceleration of about 0.5 g or more; however, further testing will be required to verify the design techniques for avoiding positive expulsion devices. (These design techniques are described at the end of the next section.) Positive expulsion devices will be required to expell gels when zero or low (less than 0.2g) helpful acceleration forces are present. For adverse accelerations, gelled propellants will also require positive expulsion devices. Unless a significant helpful acceleration is present during the expulsion process, the pressurant gas tends to core through the gel bulk to the liquid outlet leaving an unacceptably large percent of residual propellant.

There is no doubt that the screens can be used to contain a gelled propellant at one end of a tank against an adverse acceleration of one g or more. The only question was the ability to design a screen containment assembly through which the gel may be expelled against an adverse acceleration (gas in the bottom; liquid out at the top).

In order to expel against an adverse acceleration, the screen must have a higher pressure drop to the gas than to the liquid. Newtonian fluids exhibit this property because the surface tension at the gas-liquid interfaces (at the screen pores) creates a greater pressure drop for the gas across the screen than caused by the liquid flow rate across the portion of the screen which connects to the propellant outlet by a fluid-fluid path. The upper portion of Figure 35 illustrates how pie-pan-shaped screens accomplish this feat.

The lower portion of Figure 35 illustrates another area of concern for both neat and gelled propellants, and that is whether or not the pie-pans that have had gas enter them can be completely refilled with liquid by the acceleration of the main engine. Preliminary indications are that it will be difficult to do so.

The effect of gelling a fluid on its surface tension, or whatever other property then becomes the significant parameter in controlling the gas-gel critical pressure-drop across a screen, was not apparent so the tests described in the following section were performed.

d. Screen Containment and Expulsion Tests

(1) Introduction

A series of gel expulsion tests were conducted in transparent acrylic tanks to gain further insight into the behavior of gels with propellant containment screens designed for neat (nongelled) fluids. Some expulsions were also made to evaluate the expulsion efficiency of a flat bottomed tank with and without a baffle over the gel outlet.

The two gels used for these tests were water gelled with 0.27% Carbopol 940 (an organic gelling agent) and water gelled with 5.2% Santocel Z (submicron SiO_2 particles). Characteristic flow curve for each gel through an ASTM D-1092 capillary viscometer is shown in Figures 36 and 37. Each gel had a yield stress of 1400 dyne/cm^2 as measured on a rising sphere rheometer. The Carbopol gel was colored a transparent dark blue, whereas the Santocel gel was colored an opaque red. The neat water was colored a dark green for the tests, and sawdust was floated on top of the water for some sequences. The green coloring was added to improve contrast.

(2) Testing

(a) Apparatus

The test apparatus consisted of two acrylic-walled (4.75 in. ID by 8 in. long) cylindrical tanks with flat aluminum end plates, connecting tygon tubing, and a squeeze bulb or shop air for an air pressure supply (Figure 38). Either flat or pie-pan screens were placed across the interior of the main tank and sealed at the edges approximately 2 and 4 in. from the bottom of the tank. The receiver tank had a 1.85-in.-dia, curved-disk baffle placed 0.17 in. above one outlet. Both tanks were used for expulsions in the normal and inverted positions.

The stainless-steel screens used in these tests were flat circular sections of 70 by 64 mesh (0.0065-in.-dia wire, 200 micron openings) and 18 by 18 square mesh (980 micron openings) and pie-pan shaped assemblies of 100 by 100 square mesh (0.006-in.-dia wire, 150 micron openings). The pie-pan assemblies were composed of a flat circular disk at the base with corrugated (pleated) sides to increase the surface area.

(b) Procedure

After the main tank was assembled with the screen sections of interest installed, the received tank was filled about 75% full with one of the two gels and was closed. Either a hand-operated squeeze bulb (20 psig maximum) or the laboratory air supply system (50 psig maximum) was used to fill the main tank from the bottom with gel from the received tank until the uppermost screen section had been covered by the gel. Expulsions from the main tank to the received tank were made by moving the air supply to the top of the main tank. Successive tests were made by expelling the same gel back and forth from one tank to the other.

(c) Tests and Results

A summary of the organic and particulate gel expulsion tests is given in Table 12.

1 Organic Gel

a Normal Screen Expulsion

In Test 1, the two pie-pan configuration for the main tank (shown in Figure 38) was filled to just above the upper pan surface and then expelled with shop air while in a normal upright position. The gel level dropped until a thin film covered the surface of the upper pie-pan (followed its contour), then the air cored down through the middle of both pans to the gel discharge port (Figure 39). It was estimated that approximately 10% of the volume between the upper pan and the bottom of the tank was expelled.

b Reverse Screen Expulsion

In Tests 3 and 5, the two pie-pan configuration was filled to just above the upper pan. The tank was inverted and an attempt made to expel the gel against gravitational acceleration. In each case (the fast expulsion with shop air and the slow expulsions with the squeeze bulb) only a small portion of the gel was expelled from between the pans before the air broke through and cored to the gel outlet to end the expulsion (Figure 40). About 5% of the contained gel was expelled in each case. It was noted that when the air which cored through the residual gel in the main tank came up through the gel in the receiver tank, it formed a thin vertical flow channel which left the bulk of the gel undisturbed. When the air flow was terminated, only a few residual bubbles remained in the gel in the receiver tank.

<u>c</u> Unbaffled Expulsions

In Tests 6, 7 and 8, the receiver tank was filled about 80% full and then expelled by the shop air supply until the air cored through the remaining gel to the outlet. The results of each expulsion were identical with the final surface contour of the gel sloping from the walls of the tank (2 in. above the bottom) down to the outlet (Figure 41).

It was evident that nearly all of the flow was confined to a cone with a total included angle of 90° extending up from the outlet (Figure 41). The maximum gel velocity was essentially axial and fell off rapidly as the included angle of the imaginary cone was increased. Near the end of the expulsion, the axial velocity gave the appearance of sliding progressive surface layers of the gel down into the outlet. The expulsion rates were:

	V_{exit}, in./sec	V_{tank}, in./sec	$\dot{V}$, in.^{3}/sec
Test 7	31.6	0.088	1.55
Test 8	28.5	0.079	1.40

The diameter of the tank was 4.75 in., whereas the diameter of the exit port was 0.25 in. An average gel depth of 1.5 in. (26.6 in.^{3}) remained in the tank.

<u>d</u> Baffled Expulsion

The receiver tank was filled and expelled through the baffled port. The average depth of the residual gel after coring was 0.8 in. (14.2 in.^{3}) above the raised outlet under the baffle. The gel seemed to core uniformly around the baffle disk and left a mound of gel on the disk (Figure 42). The residual gel for the flat-bottomed tank with the baffle disk was 53% of that without the baffle disk.

2 Particulate Gel

a Normal Screen Expulsion

During the initial fill attempt of the main tank in Test 1, the 100 by 100 square mesh screen (150 micron openings) in the pie-pan assembly filtered out most of the submicron SiO_2 particles so that clear, transparent red liquid appeared in the lower pie-pan. (The SiO_2 particles in the concentration required to form a gel are opaque but they are not individually discernible by the naked eye which is usually limited to greater than 40 micron particles.) At a 15 to 20 psi drop across the pie-pan, the liquid above the pie-pan remained clear and transparent and continued to accumulate at a decreasing rate. SiO_2 particle "bridging" may have caused separation.

After filling the lower pie-pan 20% with clear liquid, the liquid and the gel were expelled. The nongelled clear liquid immediately cored to the outlet through the thick gel cake below the pie-pan.

A second attempt to fill the pie-pan resulted in a cloudy liquid (not gelled) accumulating in the pan. The liquid was poured off and the tank disassembled. The 1/2-in.-thick gel cake below the pie-pan had a pasty, rubbery consistency similar to that obtained by allowing a portion of the liquid to evaporate from the normal water/Santocel Z gel.

b Unbaffled Expulsion

In an unbaffled expulsion from the receiver tank with shop air (Test 2) the gel cored when its surface-to-wall contact point was 2.0 in. above the flat bottom of the tank (Figure 43). It was estimated that the average depth of the residual gel was 1.6 in. (28.3 in.^{3}). The particulate gel did not adhere to the acrylic tank wall as much as the organic gel. As the filling of the main tank was completed for Test 3, the gel in the receiver tank cored in the same manner as described above for Test 2.

<u>c</u> Normal Flat Screen Expulsion

In Test 3, the main tank was filled and a normal expulsion made by shop air through two flat screen disks. The 18 x 18 mesh (0.0386-in. or 980 micron openings) disk and the 70 x 64 mesh disk were 2 and 4 in. above the bottom of the tank. During the fill operation, there was some liquid separation noted in the material forced through the 70 x 64 mesh screen (200 micron openings), but no separation when the gel passed through the 18 x 18 mesh screen. When expelled, up to an inch of gel was left on top of the 70 x 64 mesh screen. About 65% of the gel between the screens was expelled before the air cored to the outlet, taking about 5% of the gel below the 18 x 18 mesh screen with it (Figure 44). It is likely that coring at the center of the upper screen was encouraged by the direct impingement of the pressurizing air stream on the gel at that point.

In Test 5, the amount of gel expelled was the same with only small differences in the pattern formed by the air when it cored through the gel.

Following the Test 3 expulsion, the tank was refilled from the bottom (as usual). The screened volume filled completely, but it was noted that the residual gel on the upper screen disk (70 x 64 mesh) lifted at one edge as a flexible, cohesive cake to allow the refilling gel to move up past it. The rubbery, cohesive nature of the gel layer on the 70 x 64 mesh screen indicated that some of the fluid has been filtered from it during the original expulsion.

d Reverse Flat Screen Expulsion

In Test 4, a single reverse expulsion of the main tank was made using the screen configuration used in Tests 2, 3, and 5. It was estimated that less than 5% of the gel within the screened volume was expelled although the gel was essentially opaque and the size of cavities which touched the acrylic walls could only be guessed (Figure 45). Again some gel/liquid separation had occurred at the 70 x 64 mesh disk during filling, because, during the reverse expulsion, a cohesive layer of material lifted at one edge to allow the air to pass.

e Normal Expulsion with Slosh

Test 6 was a normal flat-screen expulsion in which a horizontal slosh motion of 3 to 4 cps was imposed on the main tank by manually shaking it. When the gas cored to the outlet, a 0.4-in. layer of gel was left on both screen disks and a 0.6-in. layer of gel (10.6 $in.^3$) on the flat end-closure of the tank (Figure 46). The slosh shaking reduced the residual gel, particularly that left on the flat screen disks.

f Baffled Expulsion

In an expulsion through the baffled outlet of the receiver tank (Test 7), the air cored to the outlet when the gel surface contacted the acrylic wall 0.9 in. above the level of the outlet (Figure 47). The average depth of the residual gel above the outlet was estimated to be 0.6-in. (10.6 $in.^3$) or 40% of that left by the unbaffled expulsion (1.6-in.).

(3) Discussion

In each expulsion test with both the organic and particulate gels, the gel viscous effects overcame the neat fluid, surface-tension effects. While less coring was experienced when normal expulsions were attempted (liquid at the bottom of the tank), in all cases the presence of the screens caused expulsion efficiencies within the screened volume of only 5 to 10%.

When the gels were being held within a volume by a screen barrier, the gel yield stress and its high, low-shear viscosity aided the surface tension and provided a strong resistance to flow through the screen. Thus a screen over a gel can keep it in the bottom of a propellant tank against several g's, but gel expulsions through screens should be avoided because of viscous coring.

To obtain high expulsion efficiencies (ca 98%) in unbaffled expulsions, it appeared that a conical gel tank end-closure and outlet with an included angle of 90° or less is required in addition to an acceleration in the direction of the gel outlet. The 90-degree included cone angle is based on noting that there was no flow to the unbaffled organic gel outlet in the region from horizontal to 45 degrees above horizontal for the flat bottomed tank. (The particulate gel was opaque so no flow pattern could be observed.)

Other gel expulsion experience has shown that gel expulsion efficiency is dependent upon the acceleration level; therefore, a narrower cone angle and steeper cone wall will probably be required for accelerations of less than 1g. One possible approach would be to increase the slope of the cone wall until the acceleration component along the wall is equivalent to that of the 90-degree included angle cone at 1g; namely, about 0.7g. Another approach would be to contour the tank end-closure and outlet to the shape taken by the organic gel when expelled without a baffle. For lower accelerations, that contour should also be made steeper.

The central baffle over the outlet showed promise for increasing the expulsion efficiency of gelled propellants with possibly much less modification to the lower end closure of the pressure vessel. The ability to use a hemispherical rather than a conical end-closure would avoid a weight penalty resulting from a heavier conical section. Since this was a test of a single design, additional work is indicated to determine an optimum design and scale-up parameters. Perhaps a small hole drilled in the center of the baffle could be used to reduce the gel residual left on the baffle.

The lower gel residual obtained when the tank was sloshing corresponds to other expulsion data which shows that any vibration, sloshing, or increased acceleration forces toward the outlet will improve the expulsion efficiency. Presumably, this is helping to break the gel's adhesion to the tank wall, overcoming the gel's yield stress, and increasing the shear forces on the gel, which has the effect of lowering its apparent viscosity (shear-thinning fluid).

Another factor which will improve gel expulsion efficiencies is the ability of the gel to hold itself together in a single flowable body (cohesive), while not sticking to the wall of the propellant tank (noncohesive or adhesive). For a given tank material, the gelling agent determines the gel's cohesive tendency.

The gel-to-wall forces are usually thought of as a property of the gel only because most tankage materials are similar in behavior; however, these forces are affected by both the gel and the wall material surface exposed to the gel. Thus, for most fuels and some oxidizers, the expulsion efficiency could be increased by coating the polished interior wall of the propellant tank with Teflon or other "slick" material, if the gel tends to adhere to the uncoated tankage material.

Of the effects mentioned--gel-to-wall adhesion, vibration and slosh, helpful acceleration, and outlet baffle, and the slope of the tank end-closure at the gel outlet--the gel adhesion characteristics and the design of the gel outlet, end closure, and baffle offer the most promising approaches to improving the expulsion efficiency of gelled propellants.

The reader is cautioned that obtaining a high expulsion efficiency is less of a problem with gels than indicated by these tests. Data from more comprehensive test programs indicate that expulsion efficiencies to 98 to 99% can be obtained with gelled propellants by suitable contouring of the bottom of the propellant tanks and with the aid of vibration and acceleration. Basically, these were screen containment tests so an available, flat-bottomed tank, known to be a poor expulsion configuration, was used to obtain relative, rather than absolute expulsion efficiency data as a by-product.

To obtain more representative data, specifically designed hardware should be used with the intended gelled propellant in the expected environment of low gravity, vibration, and slosh. The technique of simulating low-gravity expulsions by using a liquid pressurant-fluid which is slightly less dense than the propellant may be suitable for investigating this problem.

e. Slosh Tests

(1) Introduction

A series of slosh tests was performed with gelled and neat (nongelled) water to investigate the dynamic behavior of gels with respect to sloshing and to investigate the effects of high-frequency vibration on the slosh characteristics of the gels. It was anticipated at the beginning of the investigation that the dynamic behavior of the gels would be significantly different than the behavior of Newtonian fluids (water). Motion picture films were prepared to provide a visual illustration of the significant difference in the slosh behavior of gels with respect to the neat water.

(2) Test Configuration

An 18-in.-dia spherical acrylic tank was used for the slosh tests. The tank was suspended by a cable to permit freedom of horizontal movement and a hydraulic actuator with a servo-control valve was used to provide lateral excitation. The test setup is shown in Figure 48. The hydraulic actuator is on the left and an electrodynamic exciter on the right.

The two gels used for these tests were the same as used in the screen containment and expulsion tests. Water gelled with 0.27% Carbopol 940 (an organic gelling agent) and water gelled with 5.2% Santocel Z (submicron SiO_2 particles). Each gel had a yield stress of 1400 dyne/cm^2 as measured on a rising sphere rheometer.

(3) Test Procedure

A constant displacement sinusoidal excitation was applied to the tank at a fixed frequency. The excitation was continued until the tank and fluid motion became stabilized, and then the force and displacement in the actuator were recorded. The frequency was increased in unit steps of 0.1 cps and the process repeated. The slosh resonant frequencies were determined from the recorded data and visual observation. The slosh modes were then excited and motion pictures taken. Damping decay records were made of the slosh resonances by terminating the excitation and recording the resultant force and deflection decays. The slosh investigations were conducted at three fluid levels in the tank for each fluid. The levels were 30, 50, and 70% full.

High-frequency vibration was applied to the slosh tank by means of an electrodynamic exciter oriented in an axis normal to the slosh motion axis (Figure 48). Sinusoidal vibration was applied over the frequency range of 5 to 100 cps at amplitudes up to 5g. The slosh modal behaviors of the gelled fluids were observed during the applied vibration.

(4) Test Results

The slosh behavior of a fluid in a particular tank configuration can be characterized by the frequency at which slosh occurs, the motion of the fluid or mode shape, and the damping behavior or decay of oscillation. In the slosh test program, the slosh resonances were established by visual observation and by the use of the force-per-unit-displacement-response curves. The slosh tests were conducted at a fixed amplitude of displacement and the force required to maintain this displacement was measured. The peaks in the force-per-unit-displacement curves correspond to the resonances or slosh mode frequencies since the effective mass of the tank and fluid are maximum at these frequencies. The response curves for the three fluids and the three fluid levels are shown in Figures 49, 50, and 51. The height of the peaks in the response curves is indicative of the damping or reduced severity of the slosh mode.

The results of the slosh tests of neat water were in accordance with classical theories. The frequencies of slosh, the damping behavior, and the change in frequency with fluid level followed classical predictions. The slosh behavior of the two gelled waters was significantly different than the slosh behavior of water. The fundamental slosh frequencies and damping in the slosh modes were higher for the gelled waters, which is to be expected because of the increased viscosity. The mode shapes or slosh motion of the gels were completely different from water and were significantly different from each other. This difference in modal behavior occurred at all fluid levels. The Carbopol gel did not exhibit the typical pendulum motion of a fluid in a spherical tank. In the fundamental slosh mode, the fluid motion at the tank boundaries was very small and the motion consisted of the center section of fluid moving in an opposite direction to the fluid along the side of the tank. The modal behavior of the Santocel gel appeared to be a combination of the pendulum motion and the motion observed in the Carbopol gels.

The higher slosh modes of the two gels did not exhibit any characteristics of neat water slosh modes. The motion of the fluid is difficult to describe, but essentially consisted of a more circular horizontal motion with little vertical motion of the fluid surface as compared to definite vertical motion with neat water. The model behavior in the higher slosh modes is not particularly significant, but it was recorded in the motion picture film (Table 13).

The damping characteristics of the slosh modes are best described by the decay in the fluid motion when the excitation force is removed. The slosh motion of water continues for 30 to 40 cycles of oscillation after the excitation force is stopped. The slosh motion of the Carbopol gel stopped after 1 to 2 cycles of oscillation and the motion of the Santocel gel stopped within the first cycle after the excitation force was removed.

The objective of the slosh tests conducted with additional high-frequency vibration applied to the tank was to evaluate any thixotropic behavior of the gels which may influence slosh behavior. The results of this investigation showed no observable difference in slosh behavior due to an applied vibration environment. Any change in the apparent viscosity of the material which may have resulted from the applied vibration did not influence the slosh behavior.

2. Flow-Control Evaluation

Considerable prior effort has been directed to determining potential gels, characterization of these gels, and how to produce them. This effort is directed toward determining whether gels could be controlled in a conventional manner, defining the potential problems and/or advantages in gel flow control, and identifying specific areas that require more study.

The selection of the MMH/OF_2 propellant combination limits the controls effort to a relatively narrow but typical scope. Since the OF_2 is a cryogenic oxidizer, some problems are introduced. Areas such as effective bleed-in, fuel freezing, oxidizer vaporization, pressure venting, freezing of controls, two-phase flow, and vapor pocket propagation would be encountered with a cryogenic propellant in either liquid or gelled form. For this study, the primary effort is to evaluate the gelled propellant as compared to the neat propellant; therefore, the common problems of a cryogenic system will not be discussed in detail except as is necessary to define areas in which specific gel information is lacking.

The general area of material compatibility is treated similarly. Potential material compatibility problems with the propellant, regardless of whether in neat or gelled form, are not discussed. Areas where gel characteristics could cause a peculiar problem are identified.

a. Gel Characteristics

The distinguishing characteristic of a gel is that it is a non-Newtonian fluid. A Newtonian fluid at constant temperature has a constant viscosity. The apparent viscosity of a gelled propellant is a function of temperature, but in addition, the apparent viscosity changes as a function of shear rate. With a gel, the ratio of shear stress to shear rate (apparent viscosity) decreases as the shear rate increases. This gel characteristic, along with the fact that it has a yield strength, are the unique properties that offer potential advantages for gelled propellants in rocket engine systems.

b. Control System Evaluation

Typical control systems for the specified application of lunar ascent, lunar descent, and 15-month space probe are shown on Figure 52 and 53. With the primary intent of this study being an evaluation of typical systems, no system optimization was attempted. The systems shown are patterned after those presently used or proposed except for changes necessary to accommodate a cryogenic oxidizer. For the two lunar missions, the systems could be essentially the same, with the only differences being in thrust levels and throttling requirements. Since the use of a gel versus use of a liquid has no effect on the pressurization system, only the system downstream of the propellant isolation check-valves has been reviewed.

The basic systems are capable of essentially the same transient and steady-state performance with both liquids or gels as reported in the section on hydraulic transients. The intent of this section is to identify areas where some differences are expected and define expected effects of using the gelled propellants.

(1) System Filling and Bleed-In

With gelled propellants, initial filling and bleed-in will require more attention to detail than that required for liquids. With a liquid, static propellant head and high point bleed will provide a bleed-in system. With the gel, some positive pressure will be required and the location for bleed ports will be a function of the flow passages rather than physical orientation. Figure 54 illustrates this comparison. With the liquid, the gas pocket will form at the top of the loop. With the gel, the gas pocket will be pushed ahead of the gel column at the closed valve. This effect will be a function of gel viscosity and flow passage size.

Bleed-in is not expected to be a problem except if the gel were used as a valve actuation fluid. The potential problem with actuation systems is discussed in Section c, (5), (a).

(2) Heat-Transfer Effects

The potential problems as a result of heat-transfer effects for control components are not peculiar to gelled propellants; however, the characteristics of the gels are not understood to the extent necessary to define a comparative magnitude of potential problems.

The items of concern are fuel freezing and oxidizer vaporization. In a bipropellant valve, heat interchange between propellant cavities and heat soak-back from injector and chamber can occur. A most likely effect is vaporization of the cryogenic oxidizer which can cause problems with two-phase flow restart and require line venting to keep pressure to an acceptable level. This is a problem common to both neat and gelled OF_2. The unknowns that cloud this phenomenon for gels are the nature of vapor pocket formation and propagation of thermal gradients in the gel.

(3) Decontamination and Cleaning

Decontamination and cleaning of the system is a potential problem with the gelled propellants. This aspect would be of particular significance on lunar applications where the engine system may go through three firing-cleaning cycles prior to actual flight. The basic difficulty envisioned is in removing all the residual gel from areas of low flow velocity such as abrupt changes in suction of flow direction.

Work to date with nonmetallized gels indicates that successful cleaning can be accomplished by conventional flushing using a suitable flushing liquid. With the selected propellants, water and alcohol are satisfactory for the fuel and water will also dissolve the oxidizer gelling agent. Care must be exercised to ensure removal of all OF_2 before water is introduced into the oxidizer system, since water and OF_2 are hypergolic. The amount of flushing required will be a function of hardware condition. If the hardware has dried, dissolving and removing the residual film will be more difficult for the LiF gelling agent or the MMH.

An undesirable aspect of flush-cleaning is the introduction of water into a cryogenic system. Although subsequent dehydration should remove residual moisture, there remains a possibility of some moisture being trapped which could form ice or explosive mixtures when the system is used again. In view of this possibility, the frozen ClF_5 gelling agent is preferred over LiF. One potential method would be to allow the oxidizer to evaporate and then flow gaseous N_2 through the system at high velocity. The very fine lithium fluoride particles should be picked up and carried out of the system by the gas flow if they do not adhere to the hardware. With the ClF_5 gelling agent, evaporation leaves a completely clean system.

Recognition of the potential decontamination and cleaning problem permits a design to minimize areas of gel entrapment and control of postfiring procedures to minimize incomplete cleaning. Thus, with early emphasis on these areas, satisfactory decontamination and cleaning would be attainable without disassembly of hardware.

(4) Leakage

Propellant leakage is a matter of concern with both liquids and gels. With the selected propellants and gelling agents, leakage should not be aggravated by use of the gels. The gelling particles used are of submicron size and are not expected to be a problem for sealing surfaces such as valve seals.

With the high apparent viscosity of the gels, liquid leakage should be less frequently encountered than with the ungelled propellant; however, vapor leakage should be essentially the same. An unknown area that may be worthy of further examination is leakage to space vacuum. As leakage continues, it may be possible, particularly with the fuel, that the gel film would thicken and solidify to block the leak path as the fuel vaporized. Thus, the small leak might be self-sealing. If this phenomenon did occur, it could be of significant benefit from the standpoint of leakage redundancy requirements.

(5) Pressure Schedule

Fairly accurate empirical pressure loss equations for tubing have been obtained from test data. Some work has been done on cavitating venturis and orifices of sizes up to about 1/4 in. dia. Fairly consistent water-versus-gel test results are reported for both venturis and orifices (Ref D17). No information has been found relating to pressure drops through complex restrictions such as a poppet valve. Another significant factor affecting system sizing is the laminar versus turbulent flow regimes of gels. Turbulent flow is initiated at considerable higher velocities with a gel than with a liquid. The significance of this factor was discussed in Section III,B,2,b.

Another factor which bears future investigation to aid system design is the effect of temperature on apparent viscosity. The pressure drop is a function of viscosity. This temperature effect may be quite significant when trying to maintain a desired mixture ratio during throttling and also during active propellant utilization adjustments. System sizing must take into account the temperature effects as well as a velocity effects.

(6) Material Compatibility

Effect of gelled propellant on materials should not be any different than effects of the neat liquid. Data are available on material compatibility to guide selection of acceptable controls materials. There is a possibility that some materials could affect the propellant to break down or change the gel characteristics. With the selected propellants and materials used to date, no difficulty has been experienced. However, prior Aerojet-General experience with a Carbopol gel and a synthetic elastomer used as an expulsion bladder has shown gel breakdown can occur. This aspect of compatibility is not of particular significance with controls but is worthy of investigation with respect to the propellant.

c. Component Evaluation

(1) General

As shown on Figure 52 and 53, the components required included check valves, pressure relief valves, solenoid-operated shut-off valves, manually operated shut-off valves, propellant isolation valves, burst diaphragms, and propellant control valves with on-off or throttling type operation.

Keeping in mind the comparison criteria of gelled propellants versus ungelled propellants, the components could be basically the same for gelled or liquid propellants. In some components, there may be advantages to be gained by minor internal changes for gel use as related to cleaning and pressure drop as discussed previously; however, such changes would not be mandatory. The only item of particular significance relates to propellant actuation, which is discussed in a later section.

(2) Check Valves and Pressure Relief Valves

In the systems shown, the use of gelled propellants has no effect on these components. The gel would not be in contact with the components. For either the liquid or gel, the flow medium would be pressurant gas or propellant vapor; thus, operating characteristics would be the same.

(3) Burst Diaphragms

The location of the burst diaphragm in the system is such that the diaphragm would be ruptured by gas or vapor pressure rather than by the gel. The fact that the gel location in the tank is known makes this venting condition possible. This is an advantage for the gelled propellant because gas or vapor would be expelled instead of liquid propellant. For Newtonian liquids under zero-g conditions, vapor expulsion cannot be assumed without the addition of containment devices.

(4) Shut-Off and Isolation Valves

There is no apparent reason why identical valves could not be used for either liquid or gel. As mentioned previously, internal changes to assure a constant restriction and to aid effective cleaning would be desirable but are not considered mandatory.

(5) Propellant Control Valves

(a) Method of Actuation

Several conventional means of valve actuation are available: propellant actuation, separate hydraulic supply actuation, pneumatic, and electric. For gelled propellants, use of the propellant for actuation is not recommended. The cryogenic oxidizer would be a poor choice for either a gel or liquid. The fuel could be used but presents more difficult problems in gelled form. The difficulties inherent in using fuel for actuation fall in four areas: system bleed-in, dumping of actuation fluid, cleaning and functional checkout.

Failure to achieve a completely bled system can result in erratic opening and closing transients. This condition results from the controls being sized to perform with a given liquid. The introduction of gas pockets with different flow characteristics and compressibility upsets the performance until the system is completely bled-in. Use of a gel would aggravate the bleed-in problem because of the high apparent viscosity. Figures 54 and 55 tend to show the potential problem of the gel. As illustrated on Figure 54 the gel will not fill a system in the same manner as a liquid. This characteristic would have to be kept constantly in mind for a conventional system bleed-in approach. Figure 55 showing a schematic of a throttling valve, presents some idea of the complexity of the passages that would have to be filled during bleed-in.

Use of propellant for actuation requires propellant to be discharged, normally to the ambient atmosphere. In space vacuum, this is a problem because of flash vaporization which can result in liquid freezing. The vaporization and freezing phenomena for a liquid fuel are somewhat difficult to predict analytically. A gel may offer additional complexity because of the gelling agent. There are methods to overcome this problem; however, they add to system weight and complexity.

Decontamination and cleaning of a propellant actuated control is difficult with a liquid. As discussed previously, the gel may be more difficult to clean. Another aspect of this problem is that lubricant wash-out and postdecontamination residue can affect the response of controls during subsequent operation. Decontamination and cleaning, as with bleed-in, would be more difficult to achieve with a throttling control.

Functional check-out of fuel-actuated valves must be accomplished by using a performance correlation between an acceptable test fluid and the actual propellant. Obtaining a satisfactory correlation may be more difficult with gels because the gel performance would be noticeably affected by both temperature and velocity.

Some indication of the scope of problems resulting from fuel actuation is provided by recent Aerojet experience. The Apollo service module engine originally had fuel-actuated propellant valves. The above items were definite, although not exclusive, factors in the decision to convert to a pneumatic actuation system. The Transtage engine propellant valve was fuel-actuated. Recent work on an advanced version of the valve incorporates an electrical actuation system.

(b) Valve, On-Off Operation

With respect to this mode of operation, the basic valve could be the same for either liquids or gels. The only criteria for preference of the type of valve for gelled use would be the aspects of cleaning and pressure-drop variation. Two valve types were considered for possible applicability.

1 Transtage Poppet-Type Bipropellant Valve

The original valve would not be a good prospect for gelled propellant use. Fuel actuation is the primary objection. Also, this valve had the fuel and oxidizer poppets mounted on opposite ends of a common shaft with the flow such that proper functioning of the valve depended upon both fuel and oxidizer line pressures. Although the transient pressure characteristics of the gels during valve opening are apparently very similar to the liquid, valve repeatability may be affected by changes in apparent viscosity and main line bleed-in.

An improved version of this valve designed for a wide range of applications should be suitable for gel use. This version is electrically actuated using a rack and pinion. The fuel and oxidizer poppets are on separate shafts with valve porting such that main line pressure transients will not affect valve performance. This design has the inherent capability of obtaining an optimum flow transient by proper contouring of the poppets.

2 Apollo Ball-Type Bipropellant Valve

There is no apparent reason this valve would not function equally well with liquid or gel. This valve is pneumatically operated so the gel has no actuation effect. With the inherent low ΔP of a ball valve, any potential change in flow coefficient with the gel would be insignificant. The only area of concern relates to cleaning. With the particular pressure-assisted ball seal design used, complete cleaning of the seal cavities is questionable.

(c) Valve, Throttling Operation

Although there are several ways to throttle an engine, for purposes of this study only two are considered: propellant aeration and flow area control with a valve. Depending upon the required throttling range and performance, the flow area control concept can be used with or without momentum exchange.

The preferred valve for throttling control is a poppet type. Contouring of the poppet permits attainment of desired characteristics with the selected means of actuation. Considering a typical valve for this application, the use of gelled propellants should not present any significant problems. It is probable that pintle contours would be different for the gel than for the liquid; however, definition of this aspect requires more gel flow data than are currently available.

There is a potential advantage using gels for throttling operation because it is possible to operate in the laminar flow regime. If operation were in this regime, then propellant tank pressure could be lower for a given throttling range with the gels because of the direct rather than exponential flow-pressure drop relationship. A tradeoff study would be expected to verify that laminar operation is practical. Tank weight savings would be evaluated against size and weight penalties imposed by components and even lines large enough to keep flow laminar.

The use of a cavitating venturi valve for throttling is also a possibility. Test data (Ref D17) with water and gelled propellant show a consistent correlation between the liquid and gel flow rates.

Consideration of propellant aeration (i.e., density change) as a means of throttling was limited to a concept using a fluidic valve. A vortex valve could be a prime candidate for the throttling application if some unknowns were defined. Normal operation of a vortex valve has liquid flow controlled by tangential injection of a gas. The control gas mixes with the liquid, and both are expelled through the valve outlet. Thus, the liquid weight flow is decreased as control gas flow is increased until the condition of only gas flow out of the valve is reached. During the throttling range, the effluent from the valve is a gas-liquid mixture which would maintain a high injection velocity through a fixed-area injector even at low liquid weight flow rates.

Although the concept has some initial appeal, selection of such an approach is doubtful. A throttling control for the gas is required, a substantial gas supply must be carried, extended operation at low thrust would mean excessive gas use, and the aerated propellant may create some hydraulic and combustion stability problems. With respect to gels, the last item may be significant. The gas-gel interaction and mixing may be very different than that with gas-liquid. If larger pockets of gas were carried in the gel stream, combustion stability problems would be aggravated.

d. Propellant Utilization

Use of gelled propellants might permit simplification of propellant level sensing since the propellant will remain as a single mass at a known location except for a thin film left on the walls after expulsion.

A propellant utilization system is composed of a propellant-level sensing device, a propellant control device, and an electronic network to convert the propellant sensing information into command signals for the control device. Propellant level sensing could be accomplished by several means such as capacitance martix, nucleonic, and acoustic systems. For a liquid, the acoustic approach as developed by Acoustica Associates Inc., would be a preferred approach. With gelled propellants, simpler and less expensive systems might be devised using capacitance or nucleonic approaches. The fact that the gel will be a continuous mass of known form would simplify determination of the remaining propellant. Approaches that would use thermistors or hot wires might also be possible, although there are potential sensing time lags resulting from adherence of the gel to the sensing element.

The control valve used for either gel or liquid would be essentially the same--typically a butterfly valve operated over the linear portion of the flow-versus-position curve could be used in the main oxidizer feed line. In this instance, if the gel were flowing in the laminar regime, control would be more sensitive for the gel than for a liquid. With a given flow area change, the laminar gel flow rate would change more than that of the turbulent liquid flow rate.

e. Laminar Flow Injector

An area of special interest is gelled-propellant flow control in laminar-flow injectors such as the HIPERTHIN platelet design. The importance of laminar flow for gels is the characteristic of maintaining the injector pressure drop during deep throttling as previously mentioned and as discussed along with other advantages in Section III,C,3e.

Laminar flow, however, results in a much stronger dependence of flow rate on temperature than encountered with turbulent flow. The laminar flow rate is directly proportional to viscosity while turbulent flow is affected only to the extent that viscosity (through Reynolds number) changes the friction factor which, in the extreme case of fully turbulent flow, is no effect at all. Therefore, an active flow control system will be an important factor in developing a practical propulsion system using laminar flow injectors.

Because the major pressure drop and temperature variation will both occur in the metering passages of the laminar flow injector, that is clearly the best location to provide a compensating flow resistance; ideally, right at the injector face.

Since no practical method of varying the flow resistance at the injector face was apparent. Adjustments to the throttling valves, already present in such a system, would provide the necessary flow compensation.

The relation between laminar injector pressure drop and injector propellant temperatures is not known; various power-law relationships are considered possible. Whether the linear relationship will be sufficiently accurate is not presently known.

The following temperature sensors are presented for information and consideration for this temperature sensing requirement. The linear resistance thermometers considered are nickle, platinum, copper, tungsten and iridium; for linear measurement nickel is favored because it has a large temperature coefficient: 0.0067 ohms/ohms/°C. The semiconductor diode forward voltage-current characteristics are non-linear and can provide various power-law and exponential relationships depending on the manner in which it is used. The thermistor resistance versus temperature characteristic gives an exponential decrease for linear temperature increase; however, thermistors tend to be unstable and are commonly sealed in glass to improve stability, but this tends to increase the thermal time constant. A resistance thermometer bridge is naturally nonlinear and can be shifted in various ways by attaching taps with parallel elements to the self-balancing slide wire or otherwise constructing a non-linear slide wire.

The control on laminar injector temperature using only linear sensors will be considered adequate. This control is based on linearly approximating the temperature induced viscosity changes expected in the laminar injector. The control assumes the proportionality of the viscosity temperature relationship is independent of flow rate.

The functioning of the control is described below with reference to Figure 56. The thrust level command is preset thereby positioning R_1 and R_2 at the precalibrated desired thrust level; this setting established partially open positions for valves V_F and Vo. The firing is initiated by opening start valves V_{SF} and V_{SO}. After transient start, steady-state combustion is established in the combustion chamber. After a period of time heat soakback from the combustion process warms the laminar injector causing resistors R_7 and R_8 to increase in value. Also, the propellants are warmed, decreasing their viscosity and the pressure drop across the laminar injector; the combustion chamber pressure is increased. Correction occurs as follows: The increased resistances R_7 and R_8 cause the thrust level command signals to be decreased. The decreased thrust level command signals combine with the valve position signals from R_3 and R_4 to generate error signals. The error signals operate amplifiers A1 and A2 and actuator, M1 and M2 to slightly close the valves V_f and V_o. Slight closure of these valves absorbs pressure drop across the valves thereby restoring the combustion chamber pressure to its desired value. This control process occurs almost instantaneously and continuously to control the combustion chamber pressure in spite of heat soakback into the injector and propellant viscosity changes.

f. Other Characteristics

Some of the flow control characteristics related to gelled propellants were identified in other portions of this study and are summarized below.

Switching from a neat (nongelled) propellant combination to the same propellants in a gelled form raised the design flowrates only to the extent that additional flow is required to compensate for the slightly lower specific impulse. This assumes that original design thrust must be maintained. The same flow rate may be used if a lower design thrust can be tolerated. These thrust and flow rate changes are small; usually on the order of 0.5 to 3.0%.

Based on the hydraulic transient analysis in Phase II, gelling the propellants did not cause significant changes in response times (slight increase with gels) so no change in pulse width would be expected. It is possible that different gel evaporation characteristics might change the net shut-down impulse under altitude conditions, but no data was found for those conditions.

Mixture ratio and specific impulse repeatability should be as good with gels as with neat propellants after the gelled propellants are qualified and when proper gel quality control is exercised. One possible exception would be when using a laminar-flow platelet injector because of the increased dependence of flow pressure drop on temperature. The repeatability in such a system would depend on the accuracy of a control device such as discussed in the previous section.

g. Summary

The use of MMH and OF_2 as gelled propellants poses no peculiar problems with respect to controls. From a system operation standpoint, the potential problems identified would exist with neat propellants. The difference lies primarily in a comparative magnitude of the problem. For items such as bleed-in and cleaning, the gel will be more difficult to accommodate than the neat propellant. For heat-transfer-affected areas, a relative degree of difficulty cannot be assessed at present. There is some evidence that the magnitude of the problem will be less with gels.

With respect to specific controls, no unique or special hardware would be required for gel use. The use of gelled propellants as a valve actuation medium is not advised because timing, repeatability, dumping, and cleaning difficulties would be greater. All other conventional means for valve actuation would be acceptable for gel use.

Sufficient data are available to guide system design with respect to flow losses in tubes. Data on restrictions is limited. Orifice test data with one gel provides a guideline to the extent that the orifice discharge coefficient with cavitating gel flow was between the discharge coefficients for the same orifice when flowing water cavitating and noncavitating. This relationship held true for a series of orifice configurations. The effects of viscosity, orifice diameter, and ratio of orifice diameter to line diameter on the discharge coefficient are not known. The area of pressure drop through restrictions needs further investigation before accurate system tradeoff and design studies could be undertaken with confidence.

At present, there are no control factors to discourage the use of gelled propellants. Potential advantages that may be confirmed by further work lie primarily in the areas of reduced leakage problems, simplified propellant level sensing, and lower throttling system pressures.

3. Injector Design and Throttling

a. Introduction

Injector designs have been completed for use with both neat and gelled OF_2/MMH for the following missions:

Mission	Nominal Thrust, lb	Throttle Range	Duration, sec	Restart Required
Lunar Ascent	4,000	None	418	Yes
Lunar Descent	13,000	11.0:1	450	Yes
Space Probe 1	8,000	None	544	Yes
Space Probe 2	2,670 ± 330	±12.3%	544	Yes

Conventional injector designs (triplets) were selected for this study because some test data were available for a comparison between neat and gelled propellants, but a discussion of more advanced injection concepts is also included. A comparison was also made between present injectors and the advanced concepts which are more suitable for gelled propellant operation.

The conventional injector designs for all missions, except the lunar descent engine, are very similar. A major change in design concept was required for the lunar descent engine because of the requirement for continuous throttling to 11:1.

Since most of the major design considerations (except deep throttling) pertain to all missions, the discussion will be presented in the following manner:

(1) General observations and comments which pertain to the selected designs,

(2) Items pertaining to the conventional triplet element concept include all missions except the lunar descent,

(3) Items pertaining to the momentum exchange concept refer specifically to the lunar descent mission, and

(4) A discussion of advanced injector concepts.

b. General discussion

Compatibility between materials of fabrication for the injector and the thrust chamber will not be affected by gelling the propellants. The injector materials are not affected because the gelling agent is either inert (LiF) or of a chemical nature which is similar to the propellant being gelled (ClF_5 or Colloid 8010). The thrust chamber materials are not affected because, even if the particulate gelling agent should remain in the solid phase during combustion and expansion, its concentration in the reactants is usually low (less than 3 wt%). Also, it is usually a nonreacting material, when it remains a solid, so that its temperature is equivalent to, or lower than, that of rest of the combustion products. Both of these factors contrast with the combustion of a metallized propellant combination where the weight concentration of the metal typically represents 14 to 20% of the reactants and the metal reaction (7000° to 8000°R) is the main source of heat to the thrust chamber and injector due to direct impingement and high radiant heat transfer.

A film-cooled ablative chamber was selected over a regeneratively cooled design for the missions investigated, because of probable minimum impulse requirements and gel cooling unknowns. There has been no appreciable work to determine the value of gelled propellants as a coolant in chambers and injectors. Since the effect of the thin-film, gelled-fuel residue on heat transfer is also unknown, it was not possible to predict the heat transfer during succeeding firings. If the cleaning of baked-on gel residue should prove to be a problem, the inaccessibility of the interiors of regenerative cooling lines could not be tolerated.

The selection of injector designs has been based on the assumption that any residue encountered in injector passages or orifices will not interfere with restarts. The MMH uses an organic gelling agent which is expected to leave a hard, thin film residue. Tests with similar fuels and gelling agents have demonstrated that three or four restarts are possible without any detectable change in the flow characteristics of the injector. Presumably, after many* restarts, the thickness of the films would accumulate and cause a gradual increase in flow resistance.

Submicron particles of LiF were originally selected as the gelling agent for the OF_2; however, recent data for similar particulate gelling agents have indicated that injector orifices may be clogged by the initial flow residue if restarts are attempted. Therefore, the particulate gelling agent for OF_2 will be assumed to be frozen particles of an energetic oxidizer, ClF_5. Such a selection eliminates any residue problem with particulate gelling agent because it melts and vaporizes in the injector passages following a firing. It also has the advantage of contributing to thrust chamber performance. As a result of changing the oxidizer gelling agent, it was possible to design the injectors with the assumption that gel residue would not adversely affect restart operation.

The OF_2 gelled with 9.16 wt% frozen particles of ClF_5 was designated GOF_2-E2 in sequence with OF_2 gelled with 3.4 wt% LiF, which is GOF_2-E1. It was assumed that the other physical properties of GOF_2-E2 are essentially equivalent to those of GOF_2-E1.

*The value of "many" is unknown but appears to be well in excess of ten.

With the use of the OF_2/ClF_5 gelled oxidizer, cleaning of the oxidizer circuit will not be a problem. For development testing, the MMH/Colloid 8010 gelled fuel circuit should be immediately water-purged at the end of each firing to minimize gel residue buildup. Occasional purges with hot detergent water may be required if residue buildup becomes apparent from flow data or inspection of the injector. Until the rate of residue formation is determined, developmental injectors should be designed so that all internal flow passages and orifices can be reached physically for cleaning.

It is believed that flight requirements will not have a sufficient number of restarts to cause the gelled fuel residue to be a problem. Therefore, it is expected that the requirement for access to the interior of the injector for cleaning may be eliminated for flight injectors and possibly for later developmental injectors. Good design practices of proper contour, rounded entrances, and elimination of sharp corners or fluid seals which could cause propellant entrapment should be helpful in avoiding fuel circuit cleaning problems.

Leak sealing, hardware preparation, and leak detection are not expected to be significantly changed by gelling the propellants. If gelling changes leak sealing, it is likely to improve it for the fuel.

In general, the orifice sizes for injectors using gelled propellants were selected to provide a greater pressure drop across the orifice and a higher injection velocity than for neat propellants. This was done to gain equivalent or better atomization of the gelled stream.

c. Conventional Triplet Element Injectors

A pressure drop of 60 psi for neat propellants and 100 psi for gelled propellants was selected to ensure adequate propellant atomization for the injector orifices for lunar ascent, Probe 1 (fixed thrust), and Probe 2 (shallow throttling). In each design the discharge coefficient for gelled propellants was 85% of the value used for neat propellants.

The conventional triplet injectors incorporate impinging triplet elements with two fuel streams impinging on a center oxidizer stream. The oxidizer enters the injector through a centrally located manifold and flows across the back side of the injector. The oxidizer element is located axially in the injector. The fuel enters through two manifolds spaced 180 degrees apart and located near the outer periphery of the injector. The fuel is fed from a circumferential annulus through gun-drilled feed passages which are oriented perpendicular to the axis. The close proximity of the fuel passages to the injector face should provide good cooling effect. Approximately 10% of the fuel is injected adjacent to the chamber wall for film cooling. Figure 57 shows the basic injector design. The general configuration is similar for Space Probes 1 and 2, and lunar ascent injectors. The injectors differ mainly in diameter, face pattern and number of elements required.

As mentioned in the general discussion, the injector can be built for disassembly during developmental testing and as a permanently assembled part for flight units.

Because of the cooling effect of the close proximity of the neat-fuel supply passages to the injector face, the injector body can be fabricated from nickel or aluminum for the neat propellants. The manifolds, flanges, valves and other associated hardware can be fabricated from aluminum or stainless steel.

The cooling properties of gelled propellants are not known, particularly for restarts when several thicknesses of the thin-filmed, gelled-fuel residue have been baked onto the wall of the flow passage. It has been assumed that the heat-transfer capability of the gelled MMH is adequate for injector cooling and thrust-chamber film cooling until test data become available. It is suspected, however, that the higher viscosity of the gel will reduce turbulence and, therefore, the heat-transfer coefficient for injector cooling.

Design data for each of the conventional triplet injector designs are presented in Table 14.

d. Momentum Exchange Throttling

The requirement to throttle the lunar descent engine at 11:1 is difficult to accomplish by the use of variable orifice valves. After considering the advantages and disadvantages of various concepts of deep throttling, including HIPERTHIN platelet injectors*, coaxial pintle injectors, inert gas injection, main-line injection, and momentum exchange injectors, the momentum exchange concept was chosen for its suitability and its adaptability to the triplet configuration. These throttling concepts are discussed below.

The HIPERTHIN concept is considered to be the best deep throttling injector concept for gelled propellants that was considered; but because of a lack of test data, particularly for gels, it is discussed in the next section on advanced concepts and was not selected for the more detailed

*Aerojet-General Corporation proprietary concept; patent applied for.

comparisons. The movable injector pintle concepts were rejected because of sealing complexity with the reactive oxidizer. The main-line injection technique was also eliminated on the basis of the high reactivity of the oxidizer. Inert gas injection was eliminated on the basis of the system weight penalty associated with carrying a large amount of stored gas at high pressure, particularly when the amount of throttled operation was not well defined.

The selected design, momentum exchange, utilizes impinging triplet elements (fuel-oxidizer-fuel) which maintain a relatively high velocity for the reduced propellant flow at the throttled condition. Each of the fuel and oxidizer elements incorporates both a primary and secondary flow passage. The primary flow passage is designed so that at the 11:1 throttled condition, approximately 6% of the total, full-thrust flow is delivered by the primary passage. The primary orifice size is selected to maintain a high velocity. Because the inlet pressure in the primary is not reduced by a throttling valve, its velocity actually increases as the thrust is throttled (P_c decreases). The secondary flow rate is controlled by variable orifice valves and is reduced during throttling. The primary and secondary flow streams converge within the element and are injected through a common orifice. The resultant injection velocity is maintained at an acceptable level by the momentum exchange between the high-velocity primary flow and that in the secondary flow passage.

Figures 58 and 59 present resultant velocity versus thrust for neat OF_2/MMH and gelled OF_2/MMH, respectively. For the neat propellants, the minimum velocity of OF_2 is 34.2 ft/sec at 3000 lbf, whereas the minimum velocity of MMH is 44.9 ft/sec at 3000 lfb.

For the gelled propellant, the minimum velocity of GOF_2-E2 (or GOF_2-E1) is 33 ft/sec at 3000 lbf, whereas the minimum velocity of GMMH-S1 is 43.7 ft/sec at 3000 lbf. Momentum mixing was assumed to aid in gel atomization; should this not prove to be true, then the gel inlet (and propellant tank) pressures should be increased by up to 100 psi if a significant portion of the mission is run at 3000 lbf. If most of the propellant is used at the maximum and minimum thrust levels (13,000 and 1182 lbf), then no change should be required because these gel injection velocities are consistent with those chosen for the fixed thrust injectors.

The deep throttling requirement for the lunar descent engine, utilizing the momentum exchange concept, requires higher tank pressures and higher initial pressure drops to ensure adequate velocity at the lower thrust levels.

Initially, injectors utilizing 130- and 92-triplet-type momentum exchange elements were evaluated for this engine design. Both of these patterns proved undesirable because (1) the resultant small orifice size of the primary flow passages would increase the possibility of orifice plugging, and (2) physical space limitations precluded the use of large numbers of elements. The design finally chosen and presented as Figure 20 utilizes 72-triplet-type momentum exchange elements. To eliminate interference problems for the hardware, the elements are staggered in successive rows rather than spaced in a grid pattern. It is recognized that orientation of some of the outer elements may not be optimum from the standpoint of compatibility with the chamber wall; however, the degree of compatibility can only be determined from actual testing of hardware of similar configuration, and such data are not available. If the element orientation is determined to be less than adequate, the following several methods can be utilized to improve chamber injector compatibility:

(1) Fuel elements can be arranged to direct the oxidizer toward the center of the injector in critical areas.

(2) Film-coolant fuel orifices can be placed in selected locations adjacent to the chamber wall.

(3) Orifices of selected elements, adjacent to the chamber wall, can be drilled at an angle to direct propellant flow toward the center of the chamber.

Since each fuel and oxidizer element contains both primary and secondary flow passages, fabrication is more complex than for conventional triplet-type injectors. Both the primary and secondary propellant feed passages for fuel and oxidizer were blind passages gun-drilled into the injector body perpendicular to the chamber axis. The drilled passages are fed from separate annular manifolds extending nearly 180 degrees around the outer portion of the injector body. Figure 60 shows that the inlet manifolds for the oxidizer and fuel are located 180 degrees apart on the injector. Because the feed passages do not extend entirely through the injector body and the annular manifolds extend less than 180 degrees around each side of the injector, the fuel and oxidizer are prevented from mixing within the injector body.

Oxidizer elements are oriented axially and fuel elements are oriented approximately 30 degrees to the oxidizer elements. In each case, the elements are located perpendicular to the feed passages. The body of the primary element extends through the secondary feed passage, forcing the secondary propellant to flow around the body of the primary.

Again, if gelled-fuel residue is a cleaning problem with respect to restart or extended reuse capability, the workhorse injector can incorporate a disassembly feature to facilitate mechanical hardware cleaning.

The depicted concept shows that the body of the primary element is threaded into the injector for easy removal. The plug, to prevent leakage of primary propellant to atmosphere, is also threaded. In addition, the injector flange is removable to afford easy access to drilled passages and annular manifolds. For flight-type hardware these items could be brazed in place.

Since the propellant feed passages for the momentum exchange concept are not located immediately adjacent to the injector face, as with conventional triplet element injectors, the face cooling capability of the propellant is not as effective. Preliminary calculations for neat OF_2/MMH indicate that the injector body must be fabricated from nickel, if no additional cooling provisions are incorporated in the design. In that case, injector face temperatures would be expected to approach 2000°F. If the injector were fabricated from an aluminum alloy with no additional cooling capabilities, melting would be expected.

If necessary, injector face temperatures can probably be reduced by incorporating cooling passages immediately adjacent to the face; however, present information is not adequate to accurately determine the ability of gelled propellants to perform this task. The effect of nucleate boiling on heat-transfer capability and the potential effect of residue from gelled propellant at shutdown could limit restart capability. Injector bodies could eventually be fabricated from aluminum alloy if regenerative cooling proves feasible. Development of a reflective or high melting point coating would reduce face temperatures for either material.

e. Advanced Injector Concepts

On the basis of performance predictions made during this study, it became evident that some injector concepts which have not been fired with nonmetalized, gelled propellants may offer both improved performance and reduced size and weight of the thrust chamber. These performance predictions are described in the next section of this report.

The conventional injector designs described in preceding sections were analyzed. At a chamber pressure of 100 psia, the delivered (predicted) specific impulse for the neat and gelled propellants ranged from 327.5 to 359.1 sec for thrust levels of 2670 to 13,000 lbf. To predict a minimum performance loss for neat and gelled propellants, an L* of 40 in. was required for the neat propellants and an L* of 80 in. for the gels. With a comprehensive development program, it is believed that the conventional injectors could achieve the same performance with reduced L*s of 20 and 50 in. for the neat and gelled propellants.

This increase in L* for the gelled propellants is predicted due to the fact that gels flowing from an orifice will result in larger droplets which will be more difficult to vaporize than are neat propellants. Thus, an increased chamber stay-time is required for the gels to obtain the same percentage of theoretical performance as is predicted for the neat propellants.

From a system viewpoint, L*s of 50 to 80 in. for the gelled propellants are undesirable because of increased size, gimbaled moment of inertia and weight, and the larger arc in which the injector end of the chamber would swing in when gimbaled at or somewhat above the throat.

The length of the chamber is particularly severe for the lower thrust engines as shown by the upper sketch in Figure 61. This is because the axial chamber length remains essentially the same as the thrust (throat area) is increased (contraction ratio, L* and P_c constant).

The HIPERTHIN platelet injector should solve the L* problem, give better performance, and have an inherent deep throttling capability. The propellants are mechanically mixed by coming out of the injector in alternating sheets. These sheets are only a few thousandths of an inch thick, so a high injection velocity is not required. The low injection velocity also increases propellant mixing by providing a high differential velocity between that of the liquid and the reaction products. Also, the low velocity and many shallow passages in the platelet assembly result in entirely laminar flow, which allows deep throttling without the loss of injector pressure drop that accompanies the throttling of neat-propellant turbulent flow.

For example, while throttling neat propellant an order of magnitude (10:1) in a conventional injector, turbulent flow would reduce a 100-psi pressure drop to only 1 psi (100:1); the same flow reduction for laminar-flow gelled propellant would only reduce the 100-psi injector drop to somewhere between 10 and 40 psi. The 10-psi throttled pressure drop represents the lower limit of a constant viscosity laminar flow, whereas the 40-psi drop is a gel which increases rapidly in viscosity as its flow velocity is decreased.

L*s of only 10 and 15 in. should be sufficient to obtain good performance because of the excellent mixing characteristics of the platelet injectors (Figure 61).

Because the thin platelets and flow passages make a good heat exchanger, some development may be required to prevent the OF_2 from freezing the MMH. It may be possible to etch gaps in some areas between the platelets to reduce direct contact heat transfer, if it proves to be a problem.

A further reduction in main thrust chamber size can be obtained while improving performance by going to a gas-gas combustion cycle. The size of the thrust chamber is the same for both neat and gelled propellants since the materials enter as gases although the gas generators for the gelled propellants will probably require longer stay-times than those for neat propellants. Either conventional or platelet injectors could be used for the gas generators and the main thrust chamber. Simple head end gimbaling could be used by developing hot-gas bellows universal joints for the gas generator products.

Good performance for a developed gas-gas cycle should be attainable with a main thrust chamber L* of 8 in. for both the neat and gelled propellants (Figure 61).

The oxidizer-rich combustion characteristics of OF_2/MMH have not been investigated. Material compatibility, therefore, cannot be effectively evaluated at this time, but it may be a potential problem.

4. Performance

a. Description of Analytical Performance Model

(1) Objective

The objective of the performance analysis is to determine and compare the delivered performance of neat and gelled OF_2/MMH propellants when employed in four different engine configurations, two of which are throttleable. Current state-of-the-art injectors of the conventional orifice and momentum exchange element types operating on a liquid-liquid cycle are compared to future advanced injector types such as HIPERTHIN platelet injectors or gas-gas cycle combustors. The performance predictions made for these two cases are considered to be reasonable estimates of the performance range achievable by the different engine configurations.

(2) Description of Analysis Method

In order to satisfy the program objective, it will be necessary to identify the source and magnitude of different performance losses and to predict delivered specific impulse from conceptual designs. The "Interaction Theory" method of performance analysis will accomplish both tasks with a minimum of error. This method differs from the classical approach in that the quantitative effects on specific impulse are considered of the injector and chamber design parameters, of the interaction between the combustion process and the nozzle expansion process, and of the interaction between the performance losses themselves. Consideration of injector/chamber design parameters permits the separation of the "combustion efficiency" into its macroscopic and microscopic components. Mixture ratio distribution performance loss is a measure of the effect on performance of local composition gradients which are on a scale greater than the typical lateral dimension of turbulence. Energy release performance loss, on the other hand, is a measure of the effect of the vaporization, diffusion, and/or the reaction processes. By separating the combustion performance loss in this manner, the effect of incomplete combustion on the nozzle expansion process can be determined. It has been found that a reduced energy release level in the combustion chamber will interact with the expansion process and result in a lower nozzle expansion efficiency. A complete description of the Interaction Theory method of analysis and prediction of liquid rocket engine performance is contained in Ref 4.

The following performance losses are considered important in describing the performance of liquid rocket engines in the present program:

(1) Nozzle Friction Loss
(2) Nozzle Geometry Loss
(3) Nozzle Heat Loss
(4) Chamber Heat Loss
(5) Chamber Friction Loss
(6) Mixture Ratio Distribution
(7) Kinetic (Recombination) Loss
(8) Energy Release Loss
(9) Coolant Performance Loss

All but the first three losses have both a chamber and a nozzle component, whose interdependence is considered by the Interaction Theory method of performance analysis. The above losses which apply to any specific engine design are evaluated, summed, and subtracted from theoretical shifting equilibrium specific impulse to get the predicted performance. A brief description of the performance losses and of their methods of calculation is discussed below in the performance model application section.

(3) Verification of Analytical Performance Model

The Interaction Theory method has been successfully applied to the performance prediction of many Aerojet engines, and has also been the key to the isolation of sources of poor performance, so that proper design modifications could be made. The Interaction Theory method has consistently predicted performance under any operating conditions to within 2% without any test data at all, and has consistently permitted performance extrapolation of test data from sea level to altitude conditions with less than 0.5% error for actual engine systems. Some of these applications are noted below:

(1) Isolation and quantitative determination of performance losses for both N_2O_4/AeroZINE 50 and ClF_3/MHF-3 propellant tests with cooled and uncooled chambers in the Phase I tests of the transpiration-cooled chambers program, Contract AF 04(611)-10922.

(2) Verification of the recommended design changes to improve the mixture ratio distribution and/or energy release losses in the Transtage, Apollo, and Titan-Gemini 624A programs.

(3) Analytical verification of the observed effect of propellant temperature on I_s for the Gemini-MOL program from the energy release portion of the Interaction Theory performance model.

b. Application of Analytical Performance Model

(1) Theoretical Performance

Figures 62 and 63 present the vacuum shifting equilibrium theoretical performance of the neat and gelled OF_2/MMH propellants for an area ratio of 40:1. The former gives theoretical performance as a function of mixture ratio at a chamber pressure of 100 psia, while the latter gives theoretical performance as a function of chamber pressure for the particular mixture ratios which result in maximum delivered performance at nominal thrust.

It should be pointed out that the theoretical performance values shown in Figures 63 are picked from Figure 62 at mixture ratios which are lower than the theoretical peak. This is because the analysis for predicted performance has shown that the maximum delivered performance will occur at the lower mixture ratios selected in Figure 63.

(2) Performance Loss Discussion

In the following paragraphs, the different performance losses and their methods of calculation are described. Their application to the current study is pointed out where necessary.

(a) Nozzle and Chamber Friction Loss (FRIC)

Nozzle and chamber friction performance loss results from the viscous effects between the gaseous boundary layer and the nozzle or chamber wall. The nozzle and chamber friction performance losses are calculated by a computer program that uses Cole's method to obtain an expression for average skin friction. Dividing the resulting drag by the propellant weight flow yields the performance loss in seconds of specific impulse. The friction performance loss is given in percent of theoretical specific impulse in Tables 15, 16, and 17.

(b) Nozzle Geometry Loss (GEOM)

Nozzle geometry loss may be attributed to the loss in thrust due to the discharge coefficient of the throat and the loss in thrust resulting from nonaxial exit momentum. The loss is calculated by a computer program which uses the method of characteristics and has options for shifting equilibrium, frozen equilibrium, or constant specific heat ratio flow conditions. The shifting equilibrium option was utilized in the present analysis. The geometry losses for all of the configurations considered were based on minimum length Rao (bell) nozzles at an area ratio A_e/A_t of 40:1. The geometry losses were determined to be a constant 1.33% of theoretical specific impulse for these configurations.

(c) Nozzle and Chamber Heat Loss (HEAT)

Heat loss from the chamber and/or nozzle will result in lower engine performance because less energy will be available for accelerating the combustion products. Although the heat loss from ablative chambers and radiation-cooled nozzles of the type considered will have only a minor effect on performance, nevertheless an estimate of the performance penalty incurred through heat losses was made for each configuration, which was based upon the effects of heat loss upon Transtage performance as given in Ref. 15.

(d) Mixture Ratio Distribution and Coolant Performance Losses (MRD)

Irregular mixture ratio distribution arises from two potential sources, namely, improper sizing of the injector circuits for the injection elements, and cooling the chamber wall with a propellant film, in this case the fuel. A stream tube analysis is made to determine the effect of irregular mixture ratio distribution on performance.

The input information required to apply the stream tube model is (1) the mass and mixture ratio distribution across the injector face, (2) the resultant momentum and direction of effluent from each element, and (3) the theoretical I_s at the desired operating condition over a suitable O/F range. This information can be readily determined for a given injector/chamber design so that appropriate stream tubes can be selected. The performance of the system is then determined by a mass-weighted average of the performance of each individual stream tube. A complete description of the model and its application is contained in Ref 4.

In the present analysis, the assumption is made that the hydraulic circuits are properly sized for each injector, so that the only mixture ratio distribution performance loss arises from the film cooling employed at the chamber wall. The mixture ratio distribution performance loss attributed to the coolant and the performance loss coming from the heat transfer between coolant and mainstream propellants are commonly combined and termed the "coolant performance loss." In this analysis, the heat transfer effects were considered negligible and the effect of the film coolant on performance was placed in the mixture ratio distribution loss column of Tables 15, 16, and 17.

(e) Kinetic Loss (KIN)

Chemical kinetic (recombination) performance losses result from the incomplete recombination of the dissociated chemical species. This recombination lag is a function of the propellant combination, chamber pressure, mixture ratio, thrust level as reflected in nozzle size, nozzle curvature, and area ratio. Since kinetic losses are a function of mixture ratio, they will also be affected by the mixture ratio distribution in the thrust chamber. Thus, kinetic losses must be determined for each stream tube of different mixture ratio and must be combined in the ratio of their respective weight flows to the total weight flow, in order to get the total kinetic loss.

The kinetic performance losses listed in Tables 15, 16, and 17 were determined by applying the Kushida's "sudden freezing" technique, for which the reaction rate constants for the H+H and the H+F reactions were taken from Ref 16. Inherent in this analysis is the assumption that the values of these reaction rate constants for the F_2/H_2 propellants of Ref 16 are unchanged for the OF_2/MMH propellants considered herein. If this should not be true, the kinetic performance losses listed in Tables 15, 16, and 17 would be conservative, perhaps by as much as 30%.

(f) Energy Release Loss (ERL)

The energy release performance loss is that loss attributable to the fact that 100% combustion efficiency is not attained within the combustion chamber.

The performance loss that results from reduction of the available total combustion/enthalpy is usually evaluated from an unreacted propellant model based on liquid propellant vaporization characteristics as described by Priem in Ref 17. However, since the vaporization characteristics of gelled propellants are very difficult to determine short of actual testing, the energy release loss was estimated for both neat and gelled propellant cases on the basis of available test data for fluoride oxidizers with hydrazine fuels. This estimation also accounts for the effects of chamber characteristic length (L*) and a reasonable injector development program for both current and advanced concepts. The energy release loss estimates are given in Tables 15, 16, and 17 for current and future attainable values.

c. Analysis of Delivered (Predicted) Performance

Tables 15, 16, and 17 present the theoretical performance, a performance loss summary, and the delivered (predicted) performance for the four present thrust chamber configurations selected, for the neat propellants and for the LiF and ClF_5 gelled propellants, respectively. The performance of the neat propellants was analyzed for a chamber L* of 40 in., whereas the performance of the gelled propellants was analyzed for a chamber L* of 80 in. This was done to make the gels competitive with the neat propellants, because preliminary estimates of energy release loss for both showed that for a given L* the gel ERL was at least twice as high as for the neat, and was also more sensitive to changes in L*.

Tables 15, 16, and 17 show that the kinetic losses increase slightly with mixture ratio over the range considered, but increase greatly with decreasing chamber pressure as the thrust chambers are throttled. This large increase in kinetic loss is chiefly responsible for the poor performance at the deeper throttled conditions. Tables 15, 16, and 17 also show the prospective performance gains to be made by reducing the energy release loss from the values attainable by current conventional injector concepts to the much lower values estimated to be attainable by future injection techniques. These techniques include use of the HIPERTHIN injector, switching to a gas-gas cycle instead of liquid-liquid, and swirling or aerating the gelled propellant to increase droplet vaporization. Energy release loss is also sensitive to changes in chamber pressure, although not as much as is kinetic loss. This comes about as a result of poorer propellant vaporization and mixing at the lower chamber pressures, and taken together with the large kinetic losses, results in severe performance penalties for deep throttling.

Figures 64 and 65 show the variation in delivered (predicted) performance with chamber pressure of the throttlable 13,000-lbf-thrust lunar-descent and the 2670-lbf-thrust space-probe thrust chambers, respectively. The figures show that the performance of these configurations is better for the ClF_5 gel than for the LiF gel across the whole throttling range. This is dispite the larger amount of gelling agent used in the former than in the latter (9.16 wt% vs 3.4 wt%). The larger amount of gelling agent was selected to demonstrate that performance losses would be small even when three times the expected gelling agent was used. This was done because little work has been done with <u>in situ</u> gelling and frozen particles. If stable, frozen particles of ClF_5 can be made in a submicron size equivalent to Santocel Z (SiO_2 particles); then the concentration of ClF_5 can be reduced to about 3 wt%. The predicted performance of the ClF_5 gel will then approach that of the neat system very closely (about one-third the present loss).

Figure 64 also shows the rapid performance decay for deep throttling that was mentioned above. The magnitude of this performance decay is about the same for both neat and gelled propellants for both current and future injection concepts, so long as throttling is accomplished by decreasing chamber pressure.

D. TASK IV - SYSTEM DESIGN ANALYSIS

1. Space Probe Mission

The Space Probe mission was defined by the following characteristics:

Total ΔV, 7500 ft/sec,
Maximum Single ΔV, 7200 ft/sec,
Multiplicity of restarts,
Expulsion and propellant control,
Propellant weight, 13,000 lb,
Propellants are stored in four (4) spherical tanks (two (2) oxidizer, two (2) fuel) and
Be in space environment for no less than 15 months.

In performing this comparative, preliminary-design analysis between neat and gelled OF_2/MMH, it was assumed that short engine firings would be made both before and after a main firing corresponding to an ideal velocity increment of up to 7200 ft/sec. These firings would correspond to mid-course corrections, main retropropulsion, and orbit adjustment maneuvers for an orbiter mission to another planet. It was also assumed that during the coast phases of the mission the probe would be in fixed orientation with respect to the sun and that any accelerations during coast would be less than 0.10 g.

2. System Descriptions

a. Schematics

The space probe propulsion system is a regulated helium, pressure-fed, restartable system. A schematic of the system is shown in

Figure 66. High-pressure helium is expanded isothermally at the storage temperature of the OF_2 (-230°F) and fed to each propellant tank at the storage temperature of the propellant. Small component redundancy is not shown as it is common to both the neat and gelled systems and does not enter into the neat-gel comparison.

In addition to the single engine design Figure 66, three and four engine configurations were considered. The chief advantage to the single, 8000-lb fixed-thrust, gimbaled engine is higher delivered specific impulse than available from similar smaller chambers. The single larger engine is also lighter than multiple engines which provide the same total thrust. However, it may be too large to provide sufficiently accurate mid-course and orbital-adjustment velocity increments.

The use of three throttlable thrust chambers, 2670 ± 300 lb (± 12.3%), allows thrust vector control without gimbaling the chambers. Other advantages are shorter system length and possibly lower total thrust to improve accuracy in the mid-course and orbit adjust maneuvers (all three engines throttled). The three engine propulsion system schematic is shown in Figure 67. The pressurization system is the same as shown previously.

A four engine configuration was considered briefly. Its application would be limited to missions in which reliability would be the dominant factor. One pair of gimbaled, fixed-thrust chambers would be fired early in the mission to provide the mid-course corrections (4400-lb total thrust). After up to 15 months space storage, all four engines (8800-lb total thrust) would be fired to insert the vehicle into the planetary orbit. During the following few weeks or months, either pair of the engines could be used to provide orbit adjustments. The high reliability for this system comes from the ability to complete the orbit insertion maneuver on one pair of engines.

In the event of an engine malfunction, the malfunctioning engine and the one opposite would be shut down while the remaining engine pair would continue to fire to impart the required velocity increment to the spacecraft. The four engine approach improves the reliability of one engine pair by not exposing it to propellants until its use for the orbit insertion. Up to 15 months exposure to propellant residues might reduce the reliability of the engine pair used for the mid-course corrections which occur early in the mission. The four engine propulsion system is shown schematically in Figure 68. It uses the same pressurization system described previously.

b. Packaging

Packaging of the one and three engine designs was considered. The basic configuration for the tankage and pressurization system was identical for both engine designs. Two oxidizer spheres and two high-pressure helium psheres were placed as opposing pairs in the same plane above the engine injector plane. A pair of spherical fuel tanks were nested above the helium vessels as shown in Figure 69. An open support structure of four rings and four longitudinal box stringers was selected so that the oxidizer and helium storage vessels could radiate heat to space as required to maintain their -230°F storage temperature. Similarly, the fuel tanks are located toward the payload compartment which would be maintained at about the same temperature as the fuel (+70°F). It was assumed that a double-walled, aluminum radiation shield containing NRC-2 super insulation would extend across the vehicle to minimize heat transfer between the warm MMH and the cold oxidizer and helium (temperature difference of about 300°F).

The drawing for the single engine space probe propulsion system (Figure 69) shows all of the tankage mounted via sheet metal structure to the rings while the rings are held together by the longitudinal stringers. The thrust loads are transmitted to the stringers by sheet metal structure.

Head mounted gimbaling was selected for the single engine design to minimize the cryogenic oxidizer line-length which reduces boiloff and pressure losses (one bellows direct instead of two with plane changes). Throat mounting would have shortened the stage length by 10 to 12 in. but at the expense of increased line length weight and pressure drop.

The thrust structure shown for the single engine design consists of four reinforced sheet-metal arms extending from each of the four longitudinal stringers to meet in a cross on the centerline axis of the spacecraft. The head-mounted, flexual-pivoted gimbal block is mounted at the center joint with the two gimbal actuators attached to two adjacent cross members.

All of the space probe systems were designed to a 120-in. diameter and necessary length to accommodate 40:1 nozzles. For the single, 8000-lb thrust engine, the overall stage length was 186 in. for a HIPERTHIN platelet injector* using gelled propellants (L* = 15 in.). With neat propellants and the same type of injector, the stage length could be the same to 4-in. shorter (172 in. minimum for L* = 10 in.). The use of conventional orificed injectors with larger L*'s resulted in stage lengths of 190 and 210 in. for neat and gelled propellants, respectively.

The non-gimbaled, three engine layout drawing shows a preferred tank mounting structure which carries the main loads through the four longitudinal box stringers and only two of the four rings. The remaining rings stabilize the stringer structure (Figure 70). A sheet-metal structure carries the tank loads to the stringers. The tankage mount loads are more severe during boost than during spacecraft engine operation.

This method of tank mounting is suitable for both engine designs.

*Aerojet-General Corporation proprietary concept; patent applied for.

The three engine configuration results in a lighter thrust mount structure since the engines are nearer to the load bearing longitudinal stringers. The thrust loads for two of the engines are transmitted to two longitudinal stringers and the lower ring by sheet-metal structure. The third engine is mounted midway between the other two longitudinal stringers with the thrust transmitted to the stringers by a sheet metal I-beam type construction.

The use of the three non-gimbaled engines multiplies and lengthens the cryogenic OF_2 lines and the earth storable MMH lines. OF_2 boiloff and MMH freezing will be more of problem but still basically the same problem presented with the single engine configuration.

The three engine design is about 35 in. shorter than the corresponding single engine system with the gelled propellants and the platelet injector (151 in. overall). Each of the conventional injector systems was shortened by 37 in. by changing to the three engine configuration; for neat propellants 153 in. long; for gels 173 in. long.

3. System Performance

The delivered payload for the Space Probe mission was calculated for 12 cases; single- and three-engine configurations, neat propellants and gelled propellants with two concentrations of frozen ClF_5 gelling agent in the OF_2 and conventional and platelet injectors.

The two concentrations of small frozen ClF_5 particles represent the upper and lower limits of gelling agent expected to be required to gel OF_2. Two volume percent of ClF_5 (3.05 wt%) was used as the minimum concentration assuming submicron particles can be generated. This is consistent with experience using 0.007-micron particles of Cab-O-Sil H5 (SiO_2) as shown in Table 2. For an upper limit on gelling agent concentration, three times that amount was used, 6 vol% or 9.16 wt%. These gels were designated GOF_2-E3 and GOF_2-E2, respectively.

Differences in delivered payload for the same engine configurations were small in comparison to the base case of a conventional orifice injector using neat OF_2/MMH; from +3.67 to -5.24%. The small differences were not unexpected since the comparisons were between the neat and nonmetalized gelled forms of the same basic propellant combination rather than between chemically different propellant combinations.

The differences in delivered payload resulted mainly from changes in delivered (predicted) specific impulse, propellant-flow pressure losses and higher insulation allowances for the gelled propellants.

a. Single-Engine Design

For the fixed-thrust single-engine design, changing from neat to gelled OF_2/MMH resulted in a 4.1 to 5.2% reduction in delivered payload depending upon the amount of ClF_5 required to gel the OF_2. This comparison assumed the use of conventional, orificed injectors for both the neat and gelled propellants.

Using the HIPERTHIN platelet injector, changing from neat to gelled OF_2/MMH reduced the delivered payload by about 2.7 to 4.1%. As can be seen from Table 18, the payload penalty for switching to the gelled propellants was less for the platelet injector because a higher pressure drop was not required to obtain proper atomization of the gels. Also, the predicted, delivered specific impulse is higher for the platelet injector so that the delivered payload for the gelled propellants using the HIPERTHIN platelet injector was equivalent to the neat propellants using a conventional injector.

b. Three-Engine Design

With three, 2670 $\pm$ 330-lb thrust engines using conventional injectors, the payload loss which resulted from changing to gelled propellants was 4.1 to 5.1%. None of the three-engine, conventional-injector systems offered the payload capability of the base case in Table 18 (neat, single-engine, conventional injector). However, it should be kept in mind that the three-engine design results in a 3 ft shorter stage which might offer weight compensations evident only from a complete launch vehicle analysis.

For the platelet injector, the change to gelled propellants caused a 2.7 to 4.1% payload loss which was about 1% less than conventional injectors.

c. Laminar Gel Throttling

In each of the direct comparisons between neat and gelled OF_2/MMH, the use of the gelled propellants resulted in a payload penalty for the Space Probe mission. This was expected since the most advantageous use of gelled propellants is with deep throttling system whereas the Space Probe mission-definition called for little or no throttling.

The fact which is not apparent from the Space Probe analysis is that any gelled-propellant system using a HIPERTHIN platelet injector is inherently capable of deep valve-throttling without any increase in the propellant tank operating pressure. The throttling is only limited by the minimum allowable, injector pressure-drop and the propellant flow required to cool the injector face. Thus, any fixed-thrust gelled-propellant system using a platelet injector can be converted to a deep throttling system (>10:1) by simply adding throttling valves to the flow circuits.

The factors which make this possible are the laminar flow properties of the gels and the high, predicted combustion-efficiency of the platelet injectors at low propellant injection velocities. As the gel flow rate is reduced by 11:1 throttling, it appears that the GMMH-S1 injector pressure drop would be cut by a factor of 3:1 (see Volume 2, Section III,C,3,a). Thus, the single, 8000-lb thrust engine, flowing gelled propellants, would still have a 20-psid injector pressure drop when valve throttled to only 727-lb thrust. In the throttled condition, precise midcourse correction and orbit adjustment maneuvers could be performed.

Rather than obtaining propellant mixing by high velocity impingement, the platelet injector obtains high oxidizer-fuel contact areas by mechanically producing thin, closely spaced sheets of the propellants. The uniform, closely spaced flow channels of a typical HIPERTHIN platelet injector* are evident in Figure 71. The ability to machine integral baffles by contouring the injector face allows added development flexibility.

Although laminar flow can be obtained with ungelled propellants in the platelet injectors, the constant viscosity of the Newtonian fluid results in a 1:1 direct proportionality between flow rate and injector pressure drop. Assuming a minimum allowable injector pressure drop of 20 psid at the 11:1 throttled condition, a 220-psid drop would result at full thrust causing an increased propellant tank and pressurization system operating pressure and weight penalty. Thus, for deep throttling applications, the gelled systems will probably have a higher payload capability than the neat propellant systems.

*Aerojet-General Corporation proprietary concept; patent applied for.

4. Pressure Schedule

a. Chamber Pressure

The optimum chamber pressure results in the minimum system weight; however, on the basis of previous studies of bipropellant, pressure-fed propulsion systems for Space Probe missions for the optimum chamber pressure should be within the range of 100 to 300 psia. It was assumed that the optimization would have little effect on the neat/gel comparisons and a nominal chamber pressure of 100 psia was used in each case (Table 18).

b. Injector Pressure Drops

An injector pressure drop of 60-psid was selected for the neat OF_2/MMH in conventional injectors. The 60-psid pressure drop on a chamber pressure of 100 psia was selected to ensure the development of stable, high-performing engines without extensive development testing programs.

The conventional-injector pressure drop with neat propellants of 60 psid was increased by 67% to 100 psid for the gelled propellants. The increased pressure drop provided for higher flow losses with the gels and a higher injection velocity to provide better atomization. In the HIPERTHIN platelet injectors, the pressure drop for both the neat and gelled propellants was equivalent to that for the conventional injector with neat propellants (60 psid). Since propellant atomization or contact is provided mechanically by the thin platelet flow channels, a high injection velocity is not required.

c. Line and Component Pressure Drops

Representative line and component pressure drops were tabulated for the neat OF_2/MMH and then increased for the gelled OF_2MMH.

Both line and component pressure drops were increased by 50%. The increases are somewhat arbitrary because of the wide variations in gel pressure-drop data reported in the literature and lack of data for the subject propellants. The increases are certainly adequate and could be conservative by a factor of two.

5. Components

a. Thrust Chamber Assembly

The weight of the neat-propellant, conventional-injector thrust chamber assembly was taken from Ref. 18 with appropriate scaling to the present study. Conversion from the conventional injector to the HIPERTHIN platelet injector was considered to result in a small reduction in weight as the smaller chamber more than compensated for a heavier injector. The net weight reduction was less for the gels as they required a higher L* chamber for combustion efficiencies equivalent to that of the neat propellants.

b. Propellant Tankage

(1) Description

Two equal-sized spherical tanks were used for each propellant. Ardeformed AISI301 was used for the OF_2 tanks and titanium 6Al-4V for the MMH tanks. The diameter and volume of each tank are tabulated below:

Propellant	Tank Diameter, in.	Tank Volume, ft^3
Neat OF_2	54.0	94.5
Gelled OF_2	54.5	97.1
Neat MMH	50.5	78.4
Gelled MMH	49.0	70.8

Each of the spherical propellant tanks was vacuum jacketed by a spherical shell of AA-2219* with layers of NRC-2 super insulation between the tank and the jacket. Each tank and aluminum jacket were supported by two mounting brackets set into the jacket so that the jacket shell does not support the tank. The tank was supported by wires or rods which run from the mounting brackets to the propellant tank as shown in Figure 72. For the OF_2 tanks, pressurant inlet and propellant outlet lines penetrated the jacket 45° from the top and bottom and followed around in the insulation to penetrate the propellant tank at the top and bottom.

The aluminum jacket for each tank was provided for both temperature control of the propellants and for micrometeoroid protection. The vacuum jacket and NRC-2 super insulation were required to contain the OF_2 during its prelaunch period in the earth's atmosphere. The thickness of the vacuum jacket (0.060 in.) was about equivalent to that required for micrometeoroid protection for a 15-month space mission as extrapolated from the curves for tank and bumper thicknesses in Ref 19. To reduce temperature gradients in the stored gels, despite some inevitable temperature variations on the surface of the vacuum jacket, twice as much NRC-2 super insulation was used for the gels as for the neat propellants.

	Layers of NRC-2	
Propellant	Neat	Gel
OF_2	105	210 (≈2 in.)
MMH	26	52

The aluminum shells over the MMH tanks may be used either as vacuum jackets or just as micrometeoroid shields with little or no effect on the system weight.

*AA = Aluminum alloy.

Another reason for increasing the insulation on the gelled OF_2 tank was to prevent any boil-off. Boil-off would be expected to cause variations in flow properties for the gel and should therefore be avoided. The insulation on the MMH tanks helps maintain the 300°F temperature difference between the fuel and the OF_2.

The insulation is also necessary to provide enough thermal resistance to prevent the propellants from boiling due to short periods (during firing maneuvers) when the vehicle may not be oriented with the payload pointed toward the sun. Direct solar heating of the vacuum jackets will temporarily occur but the insulation will isolate most of this heat in the vacuum jacket until the vehicle is reoriented and the heat can then be re-radiated to space before it has had an opportunity to soak into the propellant tank.

A safety factor of 1.5 on yield stress was used in the design of the propellant tanks. The yield stresses for the materials were: Ardeform AISI301 stainless steel, 240,000 psi, and titanium 6Al-4V, 150,000 psi.

The problem of maintaining proper temperature conditioning of propellants left in the feed lines after a firing was considered. It appeared unlikely that both the OF_2 and MMH could be kept from freezing or boiling for an extended period of time. Therefore, some sort of venting or purging of the propellant lines will probably be required. Several adequate but not really satisfactory methods were considered but they were not pursued because the problem appears to be common to both the neat and gelled propellants and not pertinent to the neat/gel comparison.

(2) Tank Materials Selection

The basic criteria for propellant tank material selection were:

1. High strength
2. Light weight
3. Weldable and fabricable
4. Good state-of-the-art availability
5. Propellant compatibility

The alloys considered after a preliminary qualitative analysis were as follows:

Aluminum Base	Iron (steel) Base	Titanium Base
AA-2014	AISI301 (Ardeformed)	5Al-2.5Sn
AA-2219	AM350	6Al-4V
AA-6061	AM355	8Al-1 Mo-1V
	17-7PH	
	PH15-7Mo	

(a) Aluminum Alloys

Because of their low strength-to-weight ratios in comparison to the better steel and titanium base alloys, the aluminum alloys were not strong contenders for the propellant tank materials. For the micrometeoroid shields and/or vacuum jackets, aluminum alloys were superior to either steel or titanium alloys although the particular alloy did not appear to be important as tensile strength was not a pertinent factor.

For optimizing the weight of the externally pressurized spherical vacuum jacket, the significant parameter was density divided by the square root of the Young's Modulus for the material. For aluminums, titaniums, and steels, the relative weights were 1.00, 1.29 and 1.64, respectively.

A similar comparison for the micrometeoroid bumper application (Reference 19), resulted in the following relative weights for aluminums, titanium 6Al-4V and 17-7 PH steel: 1.00, 1.18, and 1.38.

The AA-2219 was considered to be the best material for the micrometeoroid bumpers/vacuum jackets. It combines good state-of-the-art with excellent weldability (including very good repair welding characteristics and, if desired, a simple post-weld heat-treat cycle), good as-welded strength and ductility, good notch toughness, strength secondary only to AA-2014-T6 and propellant compatibility equivalent to the other alloys coupled with good resistance to stress-corrosion cracking susceptibility.

(b) Steel Alloys

The alloys AM350 and Ardeformed AISI301 have had considerable application in high-pressure tankage. The 17-7PH and PH 15-7 Mo compositions have had less application as tankage and AM355, although produced in sheet form, is less preferred than its counterpart alloy, AM350. However, the relative state-of-the-art is rated good for all five alloys. The newest alloy, Ardeformed AISI301, has had intensive development in the last few years bringing the knowledge and experience to a high level. The general corrosion-resistance of AISI301 is superior to all the other alloys, although 17-7PH and PH 15-7 Mo rank close and the machinability of all the alloys is similar since they are all basically stainless steels.

With respect to general weldability and ease of weld repair, 17-7PH, PH 15-7 Mo and AISI301 are rated best and are comparable; however, post-weld heat treatment is required for all compositions except AISI301. Post-welding heat treatment of 17-7PH and PH 15-7 Mo requires annealing at 1400°F to 1700°F followed by subzero cooling (-60°F) and hardening at 850 to 1050°F to produce weld joints of 94% or better weld strength efficiency. Dimensional changes during cooling and hardening cause an expansion of 0.004 in./in. There are no dimensional changes to account for with Ardeformed AISI301. The transformation during forming at -320°F is all factored into stretch-forming parameters and the resultant joint strengths are reliably 100% equivalent to the parent metal.

Ardeformed AISI301 offers unique reliability for welded joints that is inherent in the process. The Ardeform process includes cryogenic stretch-forming of parent metal and weld in producing tankage, thus, all units and their welds are proof-tested. Defective weldments are eliminated by the process even if passed by normal inspection prior to forming.

Although the Ardeformed AISI301 is essentially proprietary with a single source* it presents the highest strength, weldable, corrosion-resistant tankage material with maximum, reliable weld-joint efficiency. Because of these factors, Ardeformed AISI301 was selected for the OF_2 propellant tank material. Titanium alloys were not considered for the OF_2 tanks because of questionable compatibility.

(c) Titanium Alloys

The low level of the state-of-the-art and weldability experience combine to eliminate the Ti-8Aℓ-1Mo-1V alloy from further

*Arde-Portland, Inc., Paramus, New Jersey consideration, but the simplicity and benefits of a post-weld stress relief (compared to reannealing and/or aging) to produce the weldment tensile properties are evident.

The strength superiority of welded Ti-6Al-4V alloy governs its selection as the candidate alloy over the Ti-5Al-2.5Sn alloy which has slightly better welding characteristics and better weld ductility.

The 6Al-4V alloy is the best overall material. It has been widely used in pressurized tankage; has equal or better weldability (including weld repair); weld strengths closely approximate the parent metal. Also, it is the highest strength titanium alloy with good notch toughness, and has a minimum strength to weight ratio of 1,000,000. Titanium 6Al-4V was selected as the material for the MMH tanks, but could not be used for the OF_2 tanks because of questionable compatibility. Because of its high strength at lower temperatures (-230°F), the specialized titanium 6Al-4V ELI was selected for the high-pressure helium storage tanks associated with the pressurization system which is described below.

c. Pressurization System

A regulated helium pressurization system was used for the Space Probe systems (Figures 66, 67 and 68). The helium was stored at 4500 psi in two spherical titanium (6Al-4V ELI) pressure vessels at the temperature of the OF_2 (-230°F). The safety factor of 1.5 on a yield stress of 200,000 psi (at -230°F) was used in the vessel design.

By adding heat to the high-pressure helium from a fuel heat exchanger, a constant temperature expansion from 4500 to 400 psia was obtained. Before being sent through the pressure regulator, the helium was warmed to the ambient temperature of the fuel (MMH) through another portion of the fuel heat exchanger. The low-pressure helium gas was then conditioned to the temperature of the propellant it was pressurizing before entering the propellant tanks. Final conditioning of the low-pressure helium to the propellant temperatures was used to avoid venting after one firing or pre-pressurizing before another. A 30% helium reserve was provided.

The high-pressure titanium spheres in which the -230°F helium was stored were insulated with NRC-2 insulation protected by an aluminum vacuum jacket. An alternative approach would be to place the helium storage vessels in the OF_2 tanks. These approaches are believed to be approximately equivalent in weight but the latter would tend to be more operationally complex.

d. Structure, etc.

The breakdown of the weights used to account for the structure, shadow shielding, flow components and lines, electrical harness and instrumentation and a destruct system for the Space Probe propulsion system is presented as follows:

A structural weight of 275 lb was used for the single-engine configuration, but this weight was reduced to 215 lb for the three-engine configuration because of less engine mount structure. Gelling the propellants did not affect the structural weight.

An allowance was made for a thermal shield across the stage between the OF_2 and MMH tanks. The shield was assumed to consist of two 0.030-in.-thick aluminum plates mounted 1 in. apart with NRC-2 super insulation between the plates. The plates were contoured around the propellant tanks and the assembly weight was estimated to be 110 lb.

To account for the propellant and helium lines and all nonpressure-dependent flow-component weights, 90 lb was allowed. This includes pressurization system and feed system valves, etc., which were not affected by tank pressure scaling. Insulation was included in these weights.

Thirty-five pounds was estimated to cover the electrical harness, instrumentation, and destruct system. For use with the HIPERTHIN platelet injectors, the weight for an active flow control system was estimated at 10 lb for the neat propellants and 20 lb for the gels. Passive flow control was assumed to be adequate for the conventional injectors.

6. System Advantages and Disadvantages

A list of system advantages and disadvantages encountered by gelling the propulsion system propellants is presented as Table 19. Most of the advantages and disadvantages are common to each of the three missions studied; lunar Descent, lunar Ascent, and Space Probe. The exception is that the Ascent and Space Probe missions do not require deep throttling as presently specified and that advantage is lost unless the Space Probe mission finds that deep throttling is necessary to achieve accurate midcourse and orbit adjustment maneuvers. Therefore, with the propellant combination OF_2/MMH, the missions can be divided into two categories; those which require deep throttling and those which use essentially fixed thrust engines.

For the deep throttling propulsion systems, the use of a gelled propellant becomes a tradeoff between the advantages listed in Table 19 and the handling (no boil-off) and cleaning difficulties suggested by the list of disadvantages. The delivered payload for neat and gelled OF_2/MMH with HIPERTHIN platelet injectors appears to be about equal so payload capability does not affect the comparison.

For the fixed thrust propulsion systems, however, the deep valve throttling capability is no longer an advantage and the added disadvantage of a delivered payload penalty of 3 to 4% is incurred with gelled OF_2/MMH. This conclusion is based on the comparison between the neat and gelled propellants with the platelet injector.

The most advantageous application of nonmetalized gelled propellants appears to be for deep throttling systems using the HIPERTHIN platelet injector. However, its application may be limited to propellants with fairly low temperature differentials as heat transfer between the thin platelet may cause boiling or freezing.

The system advantages and disadvantages listed in Table 19 are roughly in order of importance. The reason for placing the no boil-off requirement for the gels as the primary disadvantage is that it is not apparent whether accurate gel flow control can be obtained if gel boil-off does occur. Preliminary analysis indicates that OF_2 and possibly even LF_2 may be space-stored at equilibrium temperatures equivalent to their normal boiling points by shielding from solar heating and by radiating to dark space with proper tank surface coatings. However, until this conclusion and all the aspects of ground handling, such as precooling of transfer lines and propellant tanks, are investigated in detail, the no boil-off requirement may be the most serious disadvantage for cryogenic gels because accurate flow control may not be possible without it.

When this study was initiated, it was believed that one of the chief advantages of getting a cryogenic propellant would be to reduce its boil-off rate to about one third its normal value by eliminating convective heat transfer within the propellant bulk. On the basis of a careful study of the reported literature and on Aerojet's experience, it was concluded that gelling a cryogenic propellant (OF_2 in this study) would not significantly affect its boil-off rate. Therefore, reduced boil-off was not listed as a gelled-propellant advantage nor was it used in the system study. Actually, the most conservative approach of imposing a "no boil-off" requirement on the gelled OF_2 was used.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. TASK I--PRELIMINARY INVESTIGATION

The literature review showed that most gel work was scattered, and that only Alumizine was well-characterized.

The abstracts and summary tables in Volume 2, Appendix A should be valuable in acquainting personnel with the state of the art of gelled propellants and in finding existing data on specific propellants.

It is presently believed that the highest development test priority should be given to (1) manufacturing sub-micron particles of frozen ClF_5, and gelling OF_2 with these particles.

Gelling a cryogenic propellant (LO_2 and LN_2 tests) eliminates spreading, and significantly reduces the rate of boiloff when it is spilled on a hot (ambient) surface. The hazard in spillage of LF_2, OF_2, or FLOX would be reduced greatly by these effects.

B. TASK II--PRELIMINARY ANALYSIS

Carefully planned tests should be conducted to determine the effects of size, configuration, and flow rate on flow pressure drops for various types of simple and complex flow restrictions. Only straight tube data is reasonably defined at present.

Changes in gel yield stress during long-term storage may be a problem, and gelled propellant samples should be placed in storage early in any system development program so that adequate storage and aged-material flow data is available.

Differences in start, shutdown, and throttling transients between gelled and neat propellants were minor and of a magnitude to be easily eliminated by changes in valve timings or valve characteristics.

Changes in component pressure drops can be drastically reduced during throttling by operating in the laminar regime of the gel rather than the turbulent regime of a Newtonian fluid. Even when compared to laminar Newtonian flow the gel's change in pressure drop is less because the gel's "apparent viscosity" increases to compensate as the flow is throttled back.

Both OF_2 and MMH in either the neat or gelled condition were found to be space storable for 15 months without freezing or boiling, but gelling the propellants makes it more difficult to minimize the temperature extremes seen by gel on the hot and cold sides of the tank. Radiation shields are desirable in both cases.

The evaluation of gel vaporization characteristics with respect to vapor bubble formation and propagation through the gel mass should be included in storage boiloff tests for the main tank and feed line to the thrust chamber valve.

C. TASK III--COMPONENT DESIGN ANALYSIS

1. Propellant Expulsion and Control

The series of slosh tests of gelled water resulted in the expected conclusions that the gel will raise the frequency at which the slosh modes occur and greatly dampen the slosh modes. It is significant that the modal behavior or slosh motion of gelled water is completely different from the motion of water and that slosh motion of the two different types of gel is also different. The implication of this result is that, from the viewpoint of predicting or calculating slosh behavior or slosh loads of gelled fluids, none of the available theoretical and experimental work performed to date on Newtonian fluids can be applied. Although the behavior of only two gels was tested, there is an indication that the slosh behavior of any given gel may be completely different from any other gel. Therefore, for the present, all slosh investigations of gels must be approached experimentally.

A metal screen placed over a gel can contain the propellant in the lower portion of the tank against an adverse acceleration of several g's. Care must be taken that too fine a screen is not used for particulate gels because in one test the 150-micron openings (0.006 in.) in a 100 by 100 mesh screen filtered out most of the submicron, but probably agglomerated, particles of Santocel Z from the gel, but allowed the clear fluid to pass through. Possibly, filters may not be used with particulate gels.

Screens should not be used where the gel is intended to be expelled through the screen. The pressurant will core through the gel to the outlet and result in poor expulsion efficiencies.

Several factors were found to improve gel expulsion efficiencies:

(1) Gel tank outlet end closures should be contoured or conical with an included angle of 90 degrees or less. When the thrust-to-weight ratio of the vehicle is less than one, it may be desirable to increase the slope of the outlet end-closure accordingly.

(2) A good gelling agent should be able to produce a cohesive gel which does not tend to stick to metal tank walls. If a nonadhering gel

cannot be produced, then consideration should be given to a coating such as Teflon on the smooth interior surface of the tank when propellant compatibility does not prevent it.

(3) Tests with a first-try design of a centrally located baffle over the gel outlet in a flat bottomed tank reduced gel residual to one-half or less of that for unbaffled expulsion. More work should be done to determine the pertinent scaling factors and optimum design configurations.

(4) Both accleration toward the gel outlet and horizontal slosh forces appear to improve the expulsion efficiencies of the gels.

2. Flow Control

The use of OF_2 and MMH as gelled propellants poses no major problems with respect to controls. Possible advantages would be reduced leakage and simplified propellant level sensing since the shape and position of the gel would be known.

Gelled propellant mixture ratio control may not be adequate with passive methods because of the high-temperature gradients which can be sustained across a gelled propellant during storage (no covective mixing). Active flow control devices will be required for laminar flow systems since laminar flow pressure drops are more temperature dependent than turbulent flow pressure drops. The development of an active control system appears to be well within the state-of-the-art.

As line size is decreased and gelled propellant made more viscous, a switch-over will occur in which an end-of-line bleed will be required instead of a high-point bleed as gel structure overcomes gravitational effects.

3. Injector Design and Throttling

The HIPERTHIN platelet injector seems to be the best injection concept for gelled propellants. The injection of 0.003- to 0.010-in.-thick sheets of propellant from wide but shallow, etched channels offers mechanical mixing so that complete combustion should be attainable for neat propellants in an L* of 10 in., while gels may require an L* of 15 in. The laminar gel flow which results from the shallow channels allows 10:1 throttling, while an injector pressure drop of 100 psid falls to between 10 and 40 psid. Freezing of the MMH in the platelet injector is a possible problem since about a 300°F temperature difference exists between the OF_2 and MMH. If a gelled propellant injector development is initiated, primary emphasis should be placed on HIPERTHIN platelet designs.

Gas-gas combustion also appears attractive for gelled propellants, and platelet injectors might be used in both the thrust chamber and the gas generators; however, there is a possibility of gas-generator material-compatibility problems with the hot oxidizer-rich combustion products. The evaluation of the oxidizer-rich OF_2/MMH reaction and material compatibility would be the first step in the development of a gas-gas system.

The only significant change made in designing the conventional triplet injectors and the momentum exchange triplet injector was to increase the gel pressure drop by 67% to improve the atomization of the gelled propellant. The usual neat propellant discharge coefficients were reduced 15%, when sizing gelled propellant orifices, to account for the increased viscosity of the gel.

The gelling agent for OF_2 was changed from the inert LiF to ClF_5 to prevent the LiF from clogging the injector passages and orifices following each firing. The ClF_5 will vaporize when heated and leave the interior of the injector clean so that reliable restart operation can be obtained.

Some cold-flow tests with a gel similar to the MMH/Colloid 8010 indicated that only a thin, hard film is left as a residue by the fuel and that the accumulated film does not affect flow resistance for up to three restarts. Tests should be made to determine approximately how many restarts can be made before flow resistance is increased by the accumulated gelled-fuel residue.

The cooling properties of gelled propellants are unknown. Before a conventional injector can be confidently designed, heat-transfer data should be obtained for injector regenerative cooling and thrust-chamber film cooling. These tests should include data for passages which have undergone many restarts to evaluate the effect of baked-on gelled-fuel residue.

It is believed that gelling the propellants will not affect injector or thrust chamber material compatibility because of the low gelling agent concentration and because the gelling agent is either inert or similar in compatibility to the propellant in which it is used.

4. Performance

The performance analysis predicts that fully developed conventional orifice-type injectors may require an L* of 50 in. for gelled propellants in contrast to an L* of 20 in. for comparable neat propellant performance. A 50 in. L* results in an undesirably long chamber. It appears that gelled propellant injector development efforts should be directed toward the HIPERTHIN platelet or gas-gas injection techniques. The former is predicted to provide good performance with L*s of 10 and 15 in. for neat and gelled propellants. The gas-gas main thrust chamber should only require an L* of 8 in. for either propellant, but it also has two gas generators which should be packaged adjacent to the main chamber injector.

Predicted vacuum performance for the gels using energetic gelling agents was only about 1% below that predicted for neat non-gelled OF_2/MMH when the gelled system used a large L*. The gel compositions were 90.84% OF_2 + 9.16% ClF_5 and 99.0% MMH + 1.0% Colloid 8010.*

The major performance losses for both the neat and gelled OF_2/MMH conventional injector systems were the kinetic (recombination) loss, the mixture ratio distribution loss and the energy release loss; each about 3.5-4.0% at 100 psia. The 13,000-lbf system had no mixture ratio distribution loss as no film cooling was used.

Both kinetic loss and energy release loss were sensitive to decreasing chamber pressure as throttling the 13,000-lbf chamber 11:1 raised the sum of the two losses from 7.3 to 14.85% of the theoretical specific impulse. From the high dependence of the predicted (delivered) performance on chamber pressure, it is apparent that space propulsion systems should be optimized on chamber pressure by tradeoffs between increased predicted performance and increased component weights (including the propellant feed and pressurization subsystems). Such an optimization is time-consuming and therefore, usually not performed unless there is sufficient interest in the system performance to warrant the cost. Optimizations using a fixed fraction of theoretical performance for each chamber pressure are not considered adequate.

*Colloid 8010, a modified galactomannan from Stein, Hall & Co. New York, New York

The 3.6 to 8% kinetic loss was predicted using the reaction rate constants for H+H and H+F in Ref 16 on the assumption that these reaction rates for the F_2/H_2 reaction are unchanged in the OF_2/MMH reaction. If this should not be true, the kinetic performance losses would be conservative, perhaps by as much as 30%. An effort should be made to see that these rates are properly determined and published for the OF_2/MMH reaction as a part of the OF_2/MMH test programs currently being sponsored by NASA.

D. TASK IV--SYSTEM DESIGN ANALYSIS

For a fixed-thrust pressure-fed lunar Ascent system with a HIPERTHIN injector, switching from neat OF_2/MMH to gelled OF_2/MMH reduced the delivered payload by 3 to 4%. Causes of the payload penalty were: reduced specific impulse, increased residual propellant, increased propellant-tank and pressurization system operating pressure (and weight) due to higher flow losses and increased insulation weights for the gelled propellants.

For the Space Probe mission which was essentially fixed thrust, changing from neat to gelled OF_2/MMH caused a 4 to 5% payload reduction with conventional injectors and a 3 to 4% reduction with HIPERTHIN platelet injectors.

For the 11:1 throttling descent mission, switching from neat to gelled OF_2/MMH resulted in a delivered payload change from +2% to -3% when using the HIPERTHIN platelet injectors for laminar-flow throttling. The gelled propellant payloads with the platelet injector were from 1/2 to 3% greater than that for neat propellants with a conventional momentum exchange injector. The amount of change dependent upon the gelling agent (ClF_5) concentration in the OF_2 and the minimum allowable injector pressure drop assumed in the analysis.

The results of the system design analysis were determined by using the following gel characteristics, each of which should be investigated for verification and/or improvement:

Both neat and gelled propellant delivered specific impulses will be increased by changing from conventional orificed injectors to HIPERTHIN platelet injectors.

Gel pressure drops through a typical propellant feed system (lines and components) may be up to 50% greater than for the neat propellants of interest (OF_2/MMH).

Gelling the propellants will increase the residual from about 1% to 1-1/2% of the initial loaded propellant weight.

The analysis showed that the most important areas of investigation are: (1) to demonstrate the high performance which has been predicted for the HIPERTHIN platelet injectors and their suitability for use with the gelled propellants, and (2) to develop the gelled propellants. For the propellants considered in this study, OF_2/MMH, the primary propellant development effort would be for OF_2 gelled with a minimum amount of small, frozen ClF_5 particles. Chronologically, the propellant development would be the initial task.

Gel pressure drops should also be investigated as a function of line size so that line-size, pressure-drop tradeoffs can be made to optimize the propulsion system for specific propellants and missions.

Gelled propellant residuals are another mission dependent parameter. If the gelled propellant residual were reduced from 1-1/2% to 1%, then the delivered payload would be increased by about 0.6%. Some missions may benefit from breaking down the gel near the end of the expulsion to reduce gel residual, i.e., hot gas expulsion of the OF_2 to melt the residual frozen ClF_5 gelling agent.

The propellant limitations which might be imposed by on the platelet injector inter-platelet heat transfer should be investigated. Because of the proximity of the oxidizer and fuel passages in platelet injectors, the heat transfer between the propellants may prove to be a problem with propellants which must be held at widely separated temperatures such as OF_2/MMH. Propellants with a common liquid range such as earth storables, OF_2/B_2H_6 or LF_2/LPG* would not be effected.

*LPG = Liquified petroleum gas.

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TABLE 1

DEFINITION OF DESIRED CHARACTERISTICS

I. PERFORMANCE

A. Theoretical I_s: high.

B. Density: high.

C. Combustion and expansion losses: low.

D. Hypergolicity

E. Ignition: smooth and repeatable.

II. STORABILITY

A. Storability >2 years.

B. Gel separation: minimum.

C. Material compatibility: good.

D. Bulk growth: minimum.

E. Liquid range: wide (should include space-storable ambient).

F. Slosh: minimum (i.e., high yield stress).

G. Mechanically stable (i.e., high yield stress).

H. Leak sealing ability: tank pressure across 0.25-0.50-in. dia holes.

I. Position stability in Zero g: stable in main engine shutdown and up to ACS acceleration level.

III. RHEOLOGICAL PROPERTIES

A. Flow Characteristics

(1) Shear thinning: maximum.

(2) Shear stress/shear rate temperature dependence: minimum.

(3) Boiloff characteristics

(a) Boiloff rate: minimum, <1/3 of neat propellant.

(b) Boiloff limit: high, >10%.

(c) Boiloff residue: none or nonadhering and noncompacting.

TABLE 1 (cont.)

B. Static Characteristics

(1) Yield Stress

(a) High for slosh and position stability.

(b) Low to reduce pressure drop.

(2) Handling

(a) Toxicity: low.

(b) Contamination: nonsensitive.

(c) Flash and fire point: high

(d) Nonsensitive to mechanical and explosive shock.

(3) Utilization

(a) Residuals.

1 Minimum 1%.

2 Cohesive (nonwetting).

3 Uniform.

4 Unaffected by temperature gradient.

5 Unaffected by boiloff.

IV. LOGISTICS

A. Cost: low.

B. Availability: high.

C. Mixing requirements: minimum.

TABLE 2

CAB-O-SIL H5 CONCENTRATIONS REQUIRED TO GEL SEVERAL LIQUIDS

Liquid	Gelling Agent Concentration,(1) wt%	Vol%	Yield Stress $dyne/cm^2$	Reference
LH_2	35-37	1.8-1.9	550-1210	G18
LO_2	2.85	1.54	200-208	F24
LN_2	4.6	1.7	380	G18
OF_2	4.5	3.7(2)	—	G19

(1) Gelling Agent: Cab-O-Sil H5 approximately 0.007-micron particles of pyrogenic silica (SiO_2).

(2) Larger volume concentration attributed to use of larger sized particles, 0.008 to 0.015 micron, as reported by the user. Apparently a different grade of Cab-O-Sil (other than H5) was used.

TABLE 3

PROPELLANT PROPERTIES USED IN PERFORMANCE ANALYSES

Propellant/Gelling Agent	Density lb/ft^3	T_{USED} °R	T_{NBP} °R	T_{NFP} °R
LF_2	93.91	153	153	95
Gel, 3.5% LiF	95.35	153		
with these fuels: (1)				
LH_2	4.43	36.7	36.7	25.2
Gel, 13.3% Li	5.01	36.7		
N_2H_4 Blend (2)	61.38	537	682	457
Gel, 2% CP (3)	61.51	537		
B_2H_6	32.45	195.2	325.5	195.2
Gel, 2.1% Li	32.47	195.2		
OF_2	94.91	230	230	89
Gel, 3.4% LiF	96.28	230		
with these fuels: (1)				
B_2H_6	31.20	230	325.5	195.2
Gel, 2.1% Li	31.24	230		
C_3H_6 (Propylene or propene)	45.18	230	406	158
Gel, 2% Al Octoate	45.43	230		
OF_2 gel, 9.2% ClF_5		230	230	89
MMH	54.10	537	649	397
Gel, 1% Colloid 8010	54.29	537		
FLOX-73.3	86.55	160	160	90
Gel, 3.5% LiF	88.01	160		
with				
0.52 C_3H_6 + 0.48 C_3H_8	87.4	160	410	137
Gel, 2% Al Octoate	86.4	160		
98% H_2O_2 with	89.29	537	762	491
Beryllizine 33	73.76	537	696	495

(1) Neat oxidizer with each neat fuel and gelled oxidizer with each gelled fuel.

(2) 67% N_2H_4 + 24% MMH + 9% H_2O

(3) Aerojet-General Corp. proprietary gelling agent.

TABLE 4

NEAT AND GELLED PROPELLANT THEORETICAL PERFORMANCE COMPARISON

Propellants	NEAT MR	NEAT I_s (sec)	GELLED MR	GELLED I_s (sec)	Loss (%)
Standard Expansion (P_c = 1000 to 14.7 psia)					
LF_2/LH_2	8.00	411.0	7.00	399.5	2.8
LF_2/N_2H_4 Blend	2.33	360.5	2.40	348.6	3.3
LF_2/B_2H_6	5.25	372.4	4.00	356.9	4.2
OF_2/B_2H_6	3.55	365.6	3.20	357.4	2.2
FLOX-73.3/ 0.52 C_3H_6 + 0.48 C_3H_8	4.17	350.5	4.30	338.4	3.5
OF_2/C_3H_6	3.85	346.2	4.00	335.0	3.2
				Average loss	3.2
Vacuum Expansion (P_c = 100 psia, A_e/A_t = 40)					
LF_2/LH_2	9.00	474.3	7.36	461.9	2.6
LF_2/N_2H_4 Blend	2.37	417.9	2.45	409.1	2.1
LF_2/B_2H_6	5.40	432.2	4.00	418.7	3.1
OF_2/B_2H_6	3.60	427.1	3.40	419.4	1.8
FLOX-73.3/ 0.52 C_3H_6 + 0.48 C_3H_8	4.18	407.0	4.31	396.1	2.7
OF_2/C_3H_6	3.75	402.2	3.97	391.7	2.6
OF_2/MMH	2.50	399.0	2.50	391.0	2.0
				Average loss	2.4
Using Improved OF_2 gel OF_2/MMH (OF_2 gelled by ClF_5)	2.50	399.0	2.70	397.1	0.5

Table 4

TABLE 5

PERFORMANCE LOSS SUMMARY AT DESIGN CONDITIONS

PROPELLANT	LF_2/N_2H_4 BLEND
VACUUM THRUST, LB	7300
CHAMBER PRESSURE, PSIA	95
EXPANSION RATIO	40
MIXTURE RATIO	1.91

LOSS TYPE	SECONDS OF Is
NOZZLE GEOMETRY LOSS	9.3, 4.1*
NOZZLE FRICTION LOSS	7.0, 7.5*
RECOMBINATION LOSS	8.8
ENERGY RELEASE LOSS	16.1
O/F DISTRIBTUION LOSS	3.5
TOTAL LOSSES	44.7, 40.0*
THEORETICAL SPECIFIC IMPULSE	410.7
PREDICTED SPECIFIC IMPULSE	366.0, 370.7*

*REFERS TO LOSS FOR TRANSTAGE NOZZLE LENGTH PLUS 12 IN.

TABLE 6

ESTIMATED PROPELLANT PERFORMANCE FOR THE LUNAR MISSIONS

Propellants	MR	I_s Delivered	% Theo I_s	Descent[3] (M_{PAY}/M_{VEH})	Ascent[3] (M_{PAY}/M_{VEH})
LF_2/LH_2	7.8	420	89	.371	.489
	9.0	398	84	.355	.475
Gel, 3.5% LiF/ 13.3% Li[1]	6.8	400	87	.353	.472
	8.0	388	84	.347	.467
	9.0	383	83	.345	.466
LF_2/N_2H_4 Blend	1.9	370	90	.385	.486
	2.37	342	82	.330	.458
Gel, 3.5% LiF /2% CP[2]	2.0	360	89	.349	.476
	2.45	336	82	.323	.452
LF_2/B_2H_6	4.35	370	86	.354	.481
	5.3	351	81	.336	.464
Gel, 3.5% LiF /2.1% Li	3.3	360	87	.342	.470
	4.0	343	82	.325	.453
OF_2/B_2H_6	3.1	370	87	.352	.479
	3.8	351	82	.334	.461
Gel, 3.4% LiF /2.1% Li	2.8	360	90	.340	.468
	3.4	344	82	.325	.453
FLOX-73.3/.52 C_3H_6 + .48 C_3H_8	3.45	360	91	.350	.478
	4.18	338	83	.327	.456
Gel, 3.7% LiF /2% Al Octoate	3.5	345	89	.335	.463
	4.31	325	82	.312	.441

(1) Respective gelling agents and concentrations for each preceding named propellants.
(2) Aerojet-General Corp. proprietary gelling agent.
(3) Assumes no propellant boiloff prior to use.

TABLE 6 (cont.)

Propellants	MR	I_s Delivered	% Theo I_s	Descent(3) (M_{PAY}/M_{VEH})	Ascent(3) (M_{PAY}/M_{VEH})
OF_2/C_3H_6	3.2	350	89	.336	.464
(Propylene)	3.85	330	82	.314	.443
Gel, 3.4% LiF /2% Al Octoate	3.3	340	89	.326	.454
	4.0	322	82	.306	.435
OF_2/MMH	2.1	345	87	.331	.459
	2.5	335	84	.321	.449
Improved OF_2 Gel, 9.2% ClF_5 1% Colloid 8010	2.1	340	86	.326	.454
	2.6	330	84	.315	.444
98% H_2O_2/ Beryllizine 33	0.58	345	86	.332	.460

(3) Assumes no propellant boiloff prior to use.

TABLE 7

LUNAR MISSION AND SYSTEM PARAMETERS

Mission	Descent Mission	Ascent Mission
ΔV, ft/sec	7745	6882
Propellant Weight, lb	17,500	5000
System		
F/W_{VEH}, lb/lb	0.38	0.40
W_{NVD}/F, lb/lb	0.32	0.082
W_{VD}/V_T, lb/ft^3		
LF_2/LH_2 systems	3.6	4.5
Other systems	4.3	5.0

Legend

F/W_{VEH} = Engine-thrust to vehicle-weight.

W_{NVD}/F = Nonvolume-dependent weight to engine thrust.

W_{VD}/V_T = Volume-dependent weight to tank volume.

TABLE 8

SPACE PROBE MISSION AND SYSTEM PARAMETERS

Mission	
ΔV, ft/sec	7500
Propellant Weight, lb	13,000
System	
F/W_{VEH}, lb/lb*	0.290
W_{NVD}/F, lb/lb*	0.088
W_{VD}/V_T, lb/ft^3*	
No insulation	7.9
One propellant insulated	8.4
Both propellants insulated	8.9

Legend

F/W_{VEH} = Engine-thrust to vehicle-weight

W_{NVD}/F = Nonvolume-dependent weight to engine thrust

W_{VD}/V_T = Volume-dependent weight to tank volume

*Voyager Spacecraft Propulsion, Aerojet-General Corporation, Preliminary Design Report 9610-VTF-2, 12 November 1965.

TABLE 9

PHYSICAL PROPERTIES OF THE SELECTED PROPELLANTS

	Neat OF_2		GOF_2-E1		Neat MMH		GMMH-S1	
Density (OF_2 @ nBpt) (MMH @ 77°F)	95 (lb/ft^3)	1.521 (g/cc)	96.4 (lb/ft^3)	1.545 (g/cc)	54.6 (lb/ft^3)	0.874 (g/cc)	55.1 (lb/ft^3)	0.883 (g/cc)
Freezing Point	-321°F	-223.8°C	-321°F	-223.8°C	-62.3°F	52.4°C	-62.3°F	-52.4°C
Boiling Point	-230°F	-145°C	-230°F	-145°C	192.5°F	89.5°C	192.5°F	89.5°C
Critical Temp	-72.4°F	-58°C	-72.4°F	-58°C	594°F	312°C	594°F	312°C
Yield Stress (at 77°F)	None	None	0.0145(psi)	1000($dynes/cm^2$)	None	None	0.0145(psi)	1000($dynes/cm^2$)
High Shear Visc. (at 17,300 sec^{-1})	4.1×10^{-8} $\left(\frac{lb\ sec}{in.^2}\right)$	0.28 (cp)	1.46×10^{-6} $\left(\frac{lb\ sec}{in.^2}\right)$	10 (cp)	1.12×10^{-7} $\left(\frac{lb\ sec}{in.^2}\right)$	0.77 (cp)	2.18×10^{-6} $\left(\frac{lb\text{-}sec}{in.^2}\right)$	15 (cp)
Bulk Modulus (at 77°F)	1×10^{-5}(psi^{-1})	-	1×10^{-5}(psi^{-1})	-	3.3×10^{-6} (psi^{-1})	-	3.3×10^{-6} (psi^{-1})	-
Density at -20°F	-	-	-	-	64.2(lbs/ft^3)	0.923(g/cc)	64.7(lbs/ft^3)	0.932(g/cc)
Heat Capacity (liquid)	-	-	-	-	0.7 Btu/lb-°F @ 77°F	32.25 cal/mole °C @ 25°C	0.7 Btu/lb-°F @ 77°F	32.25 cal/mole °C @ 25°C
Heat Capacity (gas)	0.16 Btu/lb-°F @ nBpt	8.6 cal/mole °C @ nBpt	-	-	0.37 Btu/lb-°F @ 77°F	17.0 cal/mole °C @ 25°C	0.37 But/lb-°F @ 77°F	17.0 cal/mole °C @ 25°C
Heat of Vaporization	82 Btu/lb @ nBpt	2.7 Kcal/mole @ 144.8°C	82 Btu/lb @ nBpt	2.7 Kcal/mole @ 144.8°C	377 Btu/lb @ 77°F	9.65 Kcal/mole @ 25°C	377 Btu/lb @ 77°F	9.65 Kcal/mole @ 25°C
Specific Heat (liquid)	0.21 Btu/lb-°F @ nBpt	11.3 cal/mole °C @ nBpt	0.22 Btu/lb-°F @ nBpt	11.7 cal/mole °C @ nBpt	-	-	-	-

TABLE 10

HEAT TRANSFER ANALYSIS SYMBOLS

Symbols	
NU	Nusselt Number
GR	Grashof Number
PR	Prandtl Number
q_{SUN}	solar irradiation Btu/in.^{2}sec
q_{rad}	heat flux radiated from tank surface Btu/in.^{2}sec °R
T_w	tank wall temperature
h_L	convective heat transfer coefficient Btu/in.^{2}sec °R
T_B	propellant bulk temperature
α_S	solar absorptivity
ε	tank surface emissivity or emissivity of shield elements
ε_1	sun side emissivity of outboard element
σ	Stefan-Boltzman constant
θ	angular location, see Figure 1
T_{SAT}	propellant saturation temperature °F
$(q/A)_{max}$	maximum heat flux in nucleate boiling
ρ_v	density of saturated vapor lb/ft^3
ρ_L	density of saturated liquid lb/ft^3
h_{fg}	heat of vaporization Btu/lb
g	local acceleration ft/sec^2
g_o	gravitational constant 32.174 ft/sec
n	number of shield elements
T_s	outboard shield temperature

TABLE 11

PRESSURE SCHEDULES

	Neat Propellants		Gelled Propellants	
System Number	3		4	
Propellant	MMH	OF_2	GMMH-S1	GOF_2-E1
Chamber Pressure, psia	86.5	86.5	88.6	88.6
Injector inlet, psia	110.9	108.3	115.9	122.5
Valve inlet, psia	111.2	109.2	116.3	124.0
Orifice discharge, psia	115.5	109.8	122.3	125.7
Orifice inlet, psia	127.0	116.9	137.7	139.4
Tank, psia	134.8	124.3	148.4	154.3
Weight flow, lb/sec	17.3	36.4	17.4	38.5

TABLE 12

SUMMARY OF GELLED WATER EXPULSIONS WITH SCREENS AND BAFFLES

Organic Gel Tests (0.27% Carbopol 940)

Test	Tank/Screens	Type of Expulsion	Air Source	Results
1	Main/2 Pans	Normal	Shop	Cored, 10% expelled
2	Main/2 Pans	Reverse	Shop	Cored, 5% expelled
3	Main/2 Pans	Reverse	Bulb	Cored, 5% expelled
3a	Receiver/None	Air injection	Shop	Thin vertical core
4	Main/2 Pans	Reverse	Bulb	Cored, 5% expelled
4a	Receiver/None	Air injection	Bulb	Thin vertical core
5	Main/2 Pans	Reverse	Shop	Cored, 5% expelled
6	Receiver/None	Open	Shop	Cored, 1.5-in. residual
7	Receiver/None	Open	Shop	Cored, 1.5-in. residual
8	Receiver/None	Open	Shop	Cored, 1.5-in. residual
9	Receiver/None	Baffled	Shop	Cored, 0.8-in. residual

Particulate Gel Tests (5.2% Santocel Z)

Test	Tank/Screens	Type of Expulsion	Air Source	Results
1	Main/2 Pans	First Fill	Bulb	100 mesh filtered liquid
1a	Main/2 Pans	Normal	Bulb	Liquid caused coring
1b	Main/2 Pans	Second Fill	Bulb	Some gel through 100 mesh
2	Receiver/None	Open	Shop	Cored; 1.6-in. residual
3	Main/2 Flat	Fill only	Shop	Satisfactory fill
3a	Receiver/None	Open	Shop	Cored, 1.6-in. residual
3b	Main/2 Flat	Normal	Shop	Cored, excessive residual
4	Main/2 Flat	Reverse	Shop	Cored, 5% expelled
5	Main/2 Flat	Normal	Shop	Cored, excessive residual
6	Main/2 Flat	Normal/Slosh	Shop	Cored, less residual
7	Receiver/None	Baffle	Shop	Cored, 0.6-in. residual

TABLE 13

LIST OF MOTION PICTURE SCENES OF NEAT AND GELLED WATER SLOSH TESTS

Fluid*	Percent Full	Frequency, cps	Mode	Comments
NW	0.3	1.2 & D	1	Introduction; slow H_2O decay
NW	0.7	1.5	1	Flat surface
NW	0.7	3.0	2	Out-of-place hump & dip
PG	0.7	2.6 & D	1	Edges lag center slightly
PG	0.7	3.4 & D	2	
PG	0.7	4.2	3	Show twice, top view
PG	0.7	---	---	Modes 1, 2, & 3 side view
OG	0.7	1.9	1	
OG	0.7	2.7	2	
OG	0.7	1.9 & D	1	Show twice, top view
OG	0.7	2.7 & D	2	With decay; then side view
NW	0.7	1.5 & 3.0	1 & 2	Sawdust on water
NW	0.5		1 & 2	Sawdust on water
PG	0.5	2.2 & D	1	Show twice; top views
PG	0.5	3.1 & D	2	Side views
OG	0.5	1.8 & D	1	Top and side views
PG				Liquid-head drain
OG				Liquid-head drain

*Fluid: NW = neat water; PG = particulate gel, 5.2% Santocel Z;
OG = organic gel, 0.27% Carbopol 940.

TABLE 14

SELECTED INJECTOR DESIGN DATA

NEAT OF$_2$/MMH MR = 2.1 ε = 40 CONTRACTION RATIO 2:1	SPACE PROBE 1 THRUST 8,000-LBF	SPACE PROBE 2 THRUST 3,000-lbf	SPACE PROBE 2 THRUST 2,670-lbf	SPACE PROBE 2 THRUST 2,340-lbf	LUNAR ASCENT THRUST 4,000-lbf	LUNAR DESCENT THRUST 13,000-lbf	LUNAR DESCENT THRUST 1,182-lbf
Pc, psi	100	112	100	88	100	100	9.4
Nominal Duration, sec.	544		544		418	450	
$\dot{W}$ Total, lb/sec.	23.2	8.7	7.75	6.78	11.6	32.7	3.875
Specific Impulse, sec.	345		345		345	345	305
Density, lb/in^3							
Oxidizer	95		95		95	95	95
Fuel	64.2		64.2		54.6	54.6	
Diameter Throat, in.	7.65		4.43		5.42	9.75	
Diameter Chbr., in.	10.82		6.26		7.66	13.81	
Pressure Drop, psi	60	76	60	46.3	60	75 PRIM 65 SEC.	165.6 PRIM .131 SEC.
Orifice Dia., in.							
Oxidizer	.045		.044		.0482	.093	
Fuel	.025		.0246		.0279	.052	
Coolant	.0222		.0244		.028		
Orifice Velocity, ft./sec.							
Oxidizer	65	73	65	57	65	75	61.5
Fuel	67	75	67	58.3	72.6	99.5	80.8
Coolant	67	75	67	58.3	72.6		
Number of Elements	221		80		100	72	

GELLED OF$_2$/MMH MR = 2.2 CONTRACTION RATIO 2:1	SPACE PROBE 1 THRUST 8,000-LBF	SPACE PROBE 2 THRUST 3,000-lbf	SPACE PROBE 2 THRUST 2,670-lbf	SPACE PROBE 2 THRUST 2,340-lbf	LUNAR ASCENT THRUST 4,000-lbf	LUNAR DESCENT THRUST 13,000-lbf	LUNAR DESCENT THRUST 1,182-lbf
Pc, psi	100	112.5	100	87.6	100	100	9.34
$\dot{W}$ Total, lb/sec	23.5	8.82	7.85	6.88	11.75	38.2	3.94
Specific Impulse, sec.	340		340		340	340	300
Density, lb/in.^{3}							
Oxidizer	96.4		96.4		96.4	96.4	
Fuel	64.7		64.7		55.1	55.1	
Diameter Throat, in.	7.72		4.45		5.45	9.83	
Diameter Chbr., in.	10.9		6.20		7.71	13.9	
Pressure Drop, psi	100	128	100	77.5	100	100 PRIM 85 SEC.	190.66 PRIM 3.97 SEC. OX 7.5 SEC. F.
Orifice Dia., in.							
Oxidizer	.0432		.0423		.0463	.095	
Fuel	.0234		.023		.026	.052	
Coolant	.0207		.0228		.026		
Orifice Velocity, ft/sec.							
Oxidizer	71.6	81	71.6	63	71.6	73.1	59.6
Fuel	74.5	83.5	74	65	80.6	98	80.5
Coolant	74	83.5	74	65	80.6		

Table 14

TABLE 15

PREDICTED PERFORMANCE SUMMARY FOR NEAT OF_2/MMH

(O/F = 2.1, A_e/A_t = 40:1, L* = 40 in.)

P_c, psia	F, lb	Vac Theo I_s, sec	Losses (% $I_{s\ theo}$) FRIC	GEOM	HEAT	KIN	MRD	Current ERL	Current Σ	Future ERL	Future Σ	Current Pred. I_s, sec	Future Pred. I_s, sec
13 K Descent Engine (No Film Cooling)													
100	13,000	396.7	1.08	1.33	0.03	3.57	-	3.75	9.76	1.50	7.51	358.0	366.9
80	10,400	395.7	1.13	1.33	0.02	3.98	-	3.98	10.44	1.61	8.07	354.4	363.8
30	3,900	393.5	1.38	1.33	0.01	5.73	-	4.95	13.40	2.10	10.55	340.8	352.0
10	1,300	390.6	1.78	1.33	-	7.68	-	6.00	16.79	2.62	13.41	325.0	338.2
8K Probe Engine (6% Fuel Film-Cooling)													
100	8,000	396.7	1.06	1.33	0.03	3.78	3.45	3.75	13.40	1.50	11.15	343.5	352.5
4K Ascent Engine (6% Fuel Film-Cooling)													
100	4,000	396.7	1.21	1.33	0.03	3.99	3.45	3.75	13.76	1.50	11.51	342.1	351.0
2.67K Probe Engine (6% Fuel Film-Cooling)													
120	3,200	397.3	1.22	1.33	0.04	3.89	3.47	3.56	13.51	1.40	11.35	343.6	352.2
100	2,670	396.7	1.27	1.33	0.03	4.18	3.45	3.75	14.01	1.50	11.76	341.1	350.0
80	2,135	395.7	1.33	1.33	0.02	4.53	3.46	3.98	14.65	1.61	12.28	337.7	347.1

Table 15

TABLE 16

PREDICTED PERFORMANCE SUMMARY FOR GELS GOF_2-1/GMMH-S1

($O/F = 2.2$, $A_e/A_t = 40.1$, $L^* = 80$ in.)

P_c, psia	F, lb	Vac Theo I_s, sec	Losses (% $I_{s\ theo}$) FRIC	GEOM	HEAT	KIN	MRD	Current ERL	Current Σ	Future ERL	Future Σ	Current Pred. I_s, sec	Future Pred. I_s, sec
13K Descent Engine (No Film Cooling)													
100	13,000	389.0	1.08	1.33	0.03	3.82	-	3.75	10.01	1.76	8.02	350.1	357.8
80	10,400	388.7	1.13	1.33	0.02	4.25	-	4.01	10.74	1.91	8.64	347.0	355.1
30	3,900	386.6	1.38	1.33	0.01	6.02	-	5.25	13.99	2.56	11.30	332.5	342.9
10	1,300	384.0	1.78	1.33	-	8.00	-	6.60	17.71	3.26	14.37	316.0	328.8
8K Probe Engine (6% Fuel Film Cooling)													
100	8,000	389.0	1.06	1.33	0.03	4.02	3.50	3.75	13.69	1.76	11.70	335.7	343.5
4K Ascent Engine (6% Fuel Film Cooling)													
100	4,000	389.0	1.21	1.33	0.03	4.23	3.50	3.75	14.05	1.76	12.06	334.3	342.1
2.67K Probe Engine (6% Fuel Film Cooling)													
120	3,200	389.4	1.22	1.33	0.04	4.08	3.51	3.52	13.70	1.64	11.82	336.1	343.4
100	2,670	389.0	1.27	1.33	0.03	4.39	3.50	3.75	14.27	1.76	12.28	333.5	341.2
80	2,135	388.7	1.33	1.33	0.02	4.75	3.52	4.01	14.96	1.91	12.86	330.6	338.7

Table 16

TABLE 17

PREDICTED PERFORMANCE SUMMARY FOR GELS GOF_2-E2/GMMH-S1

($O/F = 2.1$, $A_e/A_t = 40:1$, $L* = 80$ in.)

P_c, psia	F, lb	Vac Theo I_s, sec	Losses (% $I_{s\ theo}$) FRIC	GEOM	HEAT	KIN	MRD	Current ERL	Current Σ	Future ERL	Future Σ	Current Pred. I_s, sec	Future Pred. I_s, sec
13K Descent Engine (No Film Cooling)													
100	13,000	392.7	1.08	1.33	0.03	3.57	-	3.75	9.76	1.76	7.77	354.4	362.2
80	10,400	392.3	1.13	1.33	0.02	3.98	-	4.01	10.47	1.91	8.37	351.2	359.5
30	3,900	389.9	1.38	1.33	0.01	5.73	-	5.25	13.70	2.56	11.01	336.5	347.0
10	1,300	386.9	1.78	1.33	-	7.68	-	6.60	17.39	3.26	14.05	319.6	332.5
8K Probe Engine (6% Fuel Film Cooling)													
100	8,000	392.7	1.06	1.33	0.03	3.78	3.49	3.75	13.44	1.76	11.45	339.9	347.7
4K Ascent Engine (6% Fuel Film Cooling)													
100	4,000	392.7	1.21	1.33	0.03	3.99	3.49	3.75	13.80	1.76	11.81	338.5	346.3
2.67K Probe Engine (6% Fuel Film Cooling)													
120	3,200	393.1	1.22	1.33	0.04	3.89	3.51	3.52	13.51	1.64	11.63	340.0	347.4
100	2,670	392.7	1.27	1.33	0.03	4.18	3.49	3.75	14.05	1.76	12.06	337.5	345.3
80	2,135	392.3	1.33	1.33	0.02	4.53	3.50	4.01	14.72	1.91	12.62	334.6	342.8

TABLE 18

SPACE PROBE PROPULSION SYSTEM SUMMARY

	ONE ENGINE DESIGN				THREE ENGINE DESIGN			
	Conventional Injector		HIPERTHIN Injector		Conventional Injector		HIPERTHIN Injector	
	Neat	Gel*	Neat	Gel*	Neat	Gel*	Neat	Gel*
P_c, max (psia)	100	100	100	100	112	112	112	112
ΔP_{inj}, min/max (psi)	60	100	60	60	76	126	66	64
ΔP lines etc., max (psi)	50	75	50	75	63	84	63	84
P_T (tank) (psia)	210	275	210	235	251	322	241	260
W-TCA (lb)	197	207	192	195	210	220	205	208
W-Prop. tankage (lb)	460	528	460	515	475	547	471	523
W-Press. syst (lb)	549	711	549	609	656	834	630	673
W-Structure, etc. (lb)	510	510	520	530	450	450	460	470
W-Propellant (lb)	13000	13000	13000	13000	13000	13000	13000	13000
W-Stage (lb)	14716	14956	14721	14849	14791	15051	14766	14874
W-Prop. used (lb)	12870	12805	12870	12805	12870	12805	12870	12805
Λ, mass fraction	0.8746	0.8562	0.8743	0.8623	0.8701	0.8508	0.8716	0.8609
I_{sv} (sec)	343.5	339.9	352.2	347.7	341.1	337.5	350.0	345.3
ΔV (ft/sec)	7500	7500	7500	7500	7500	7500	7500	7500
W-Lift off (lb)	26138	25779	26562	26200	25976	25662	26460	26088
W-Payload (lb)	11422	10823	11841	11351	11185	10611	11694	11214
Δ Payload (%)	0.00	-5.24	+3.67	-0.62	-2.07	-7.10	+2.38	-1.82

OF_2 Gelled with Minimum ClF_5**

I_{sv} (sec)		342.3		350.7		339.9		348.4
W-Lift off (lb)		25911		26370		25779		26255
W-Payload (lb)		10955		11521		10728		11381
Δ Payload (%)		-4.09		+0.87		-6.08		-0.36

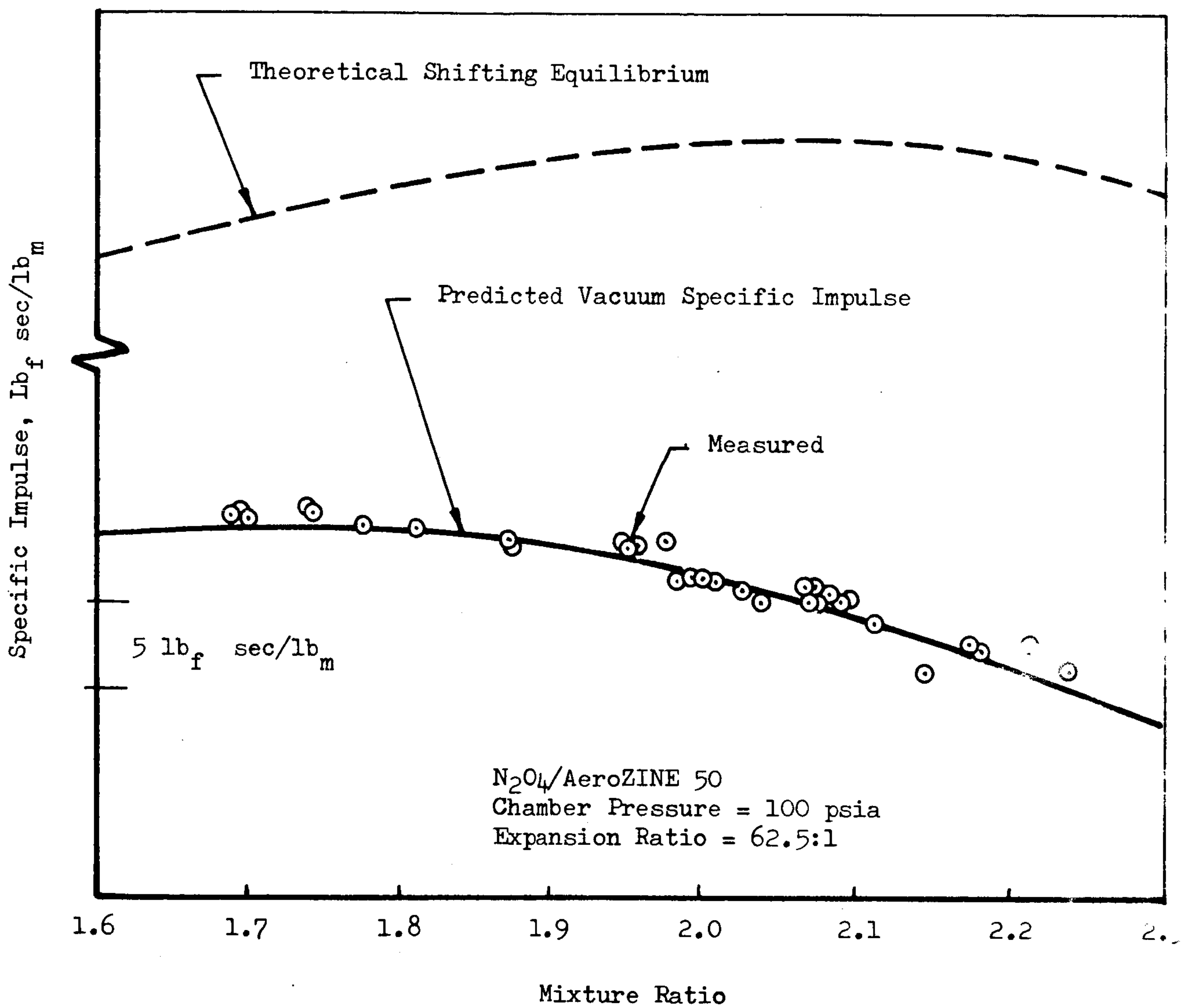
*GOF_2-E2/GMMH-S1, (0.9084 OF_2 + 0.0916 ClF_5)/(0.99 MMH + 0.01 Colloid 8010)

**GOF_2-E3/GMMH-S1, (0.9695 OF_2 + 0.0305 ClF_5)/(0.99 MMH + 0.01 Colloid 8010)

TABLE 19

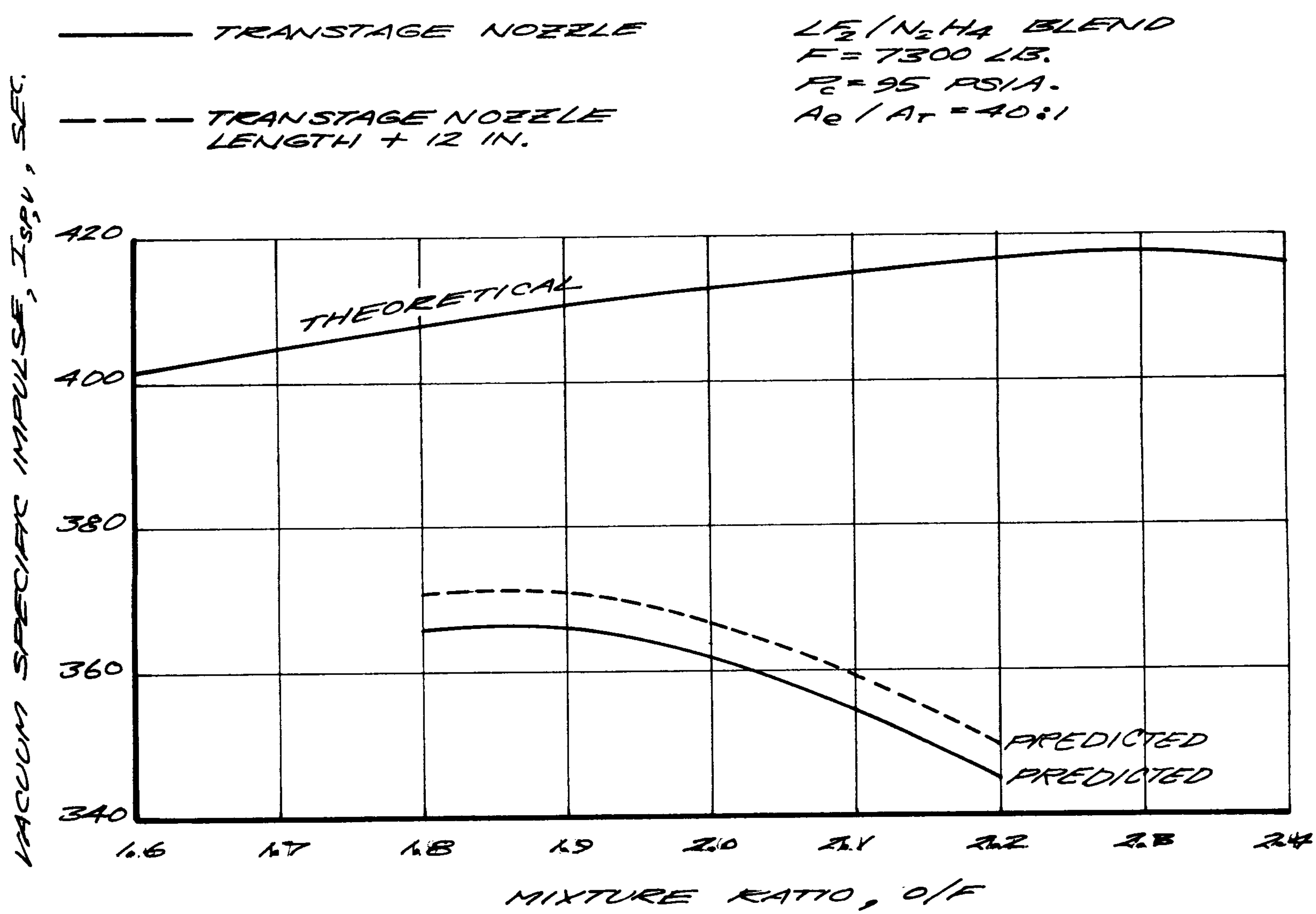
GELLED PROPELLANT SYSTEM ADVANTAGES AND DISADVANTAGES

ADVANTAGES	DISADVANTAGES
1. Deep valve throttling (HIPERTHIN)	1. Boil-off not allowed (cryogenic)
2. Reduced sloshing	2. Lower specific impulse
3. Weightlessness position control	3. More residual propellant
4. Reduced thrust/pressure overshoot	4. Higher pressure drop/larger lines
5. Reduced spillage hazard	5. Higher temperature gradients
6. May reduce fuel leakage	6. Longer L* chamber
	7. Active flow control
	8. May complicate bleed-in and fuel cleaning



Example of Verification of Performance Prediction

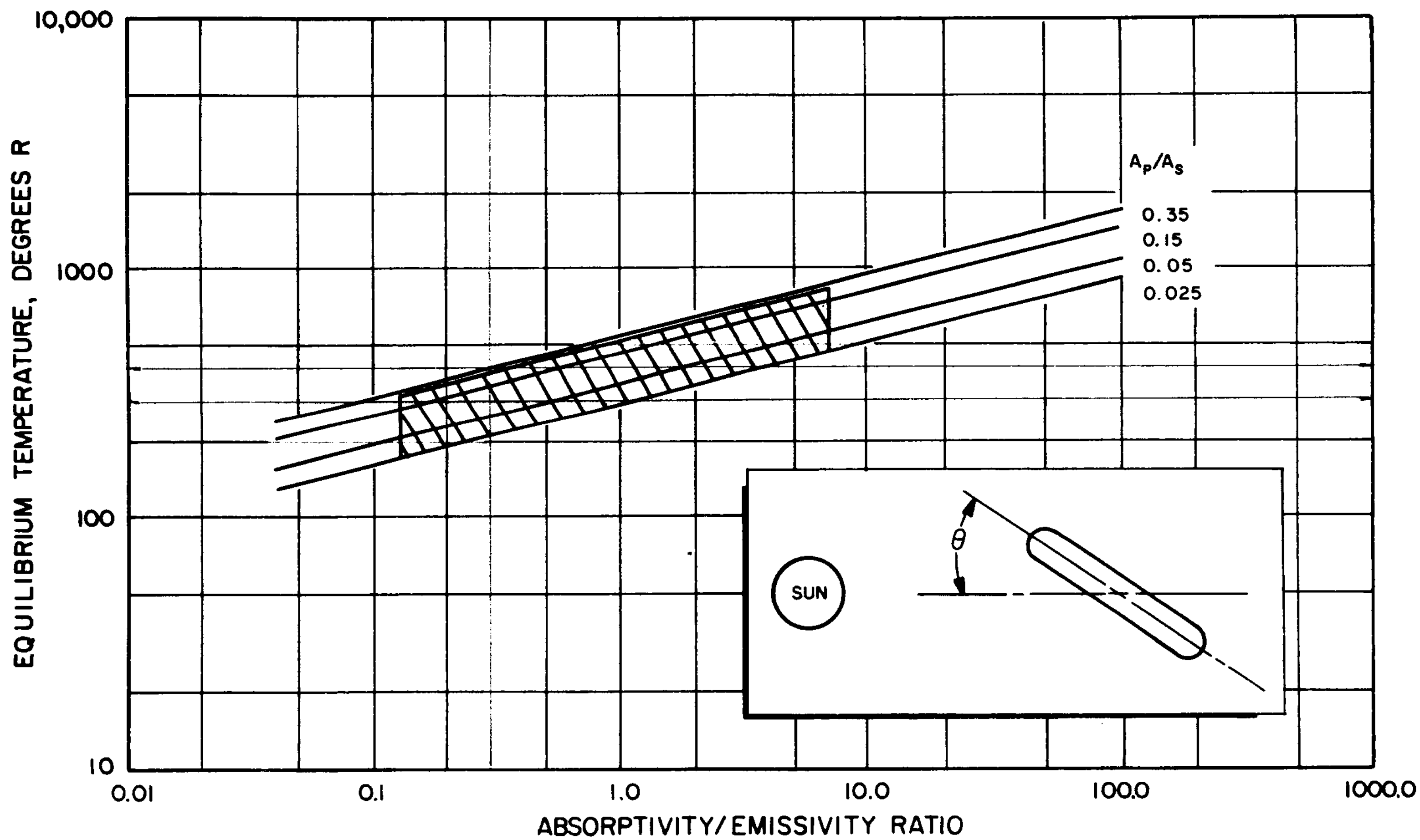
Figure 1



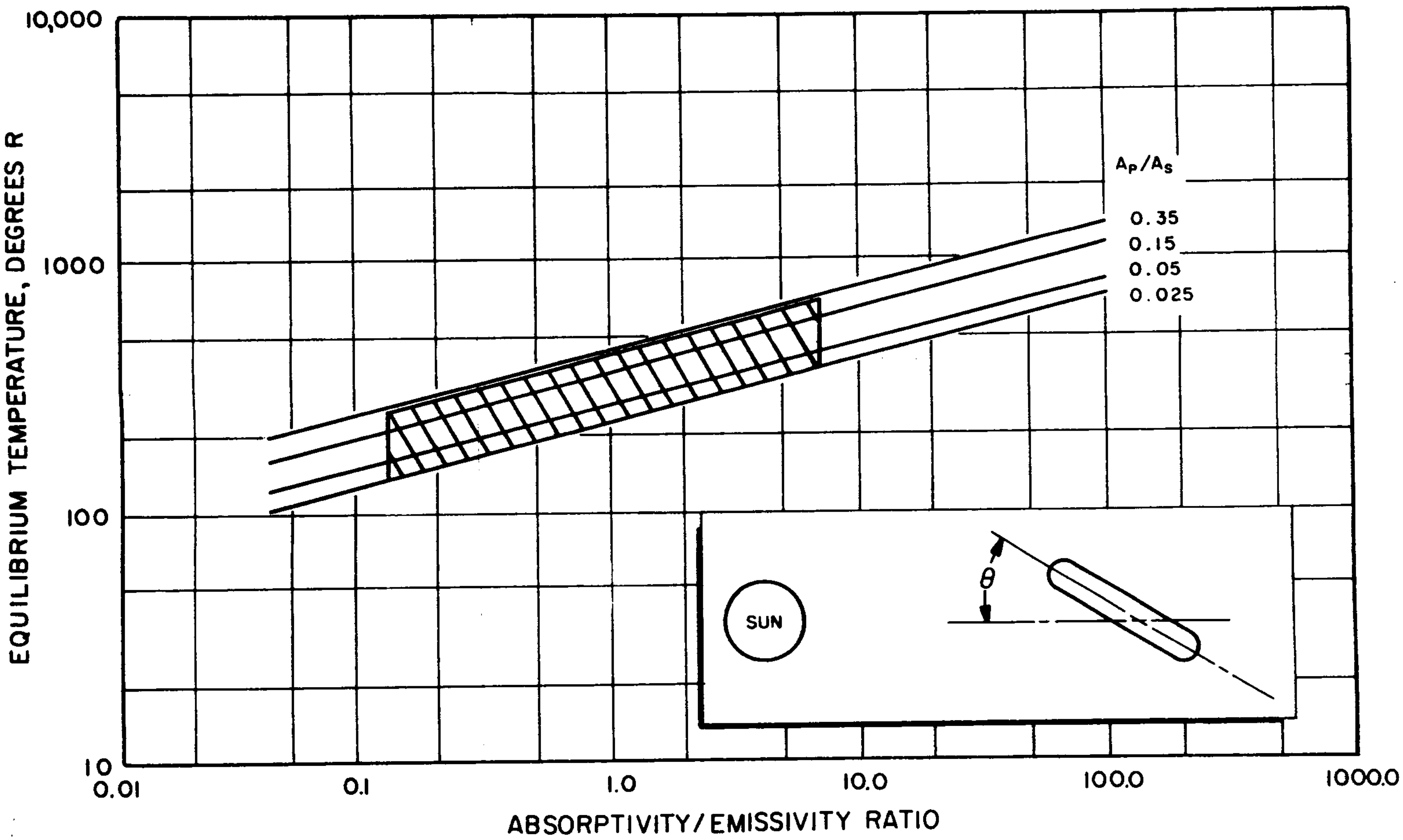
Performance Variation with Mixture Ratio

Figure 2

Figure 3

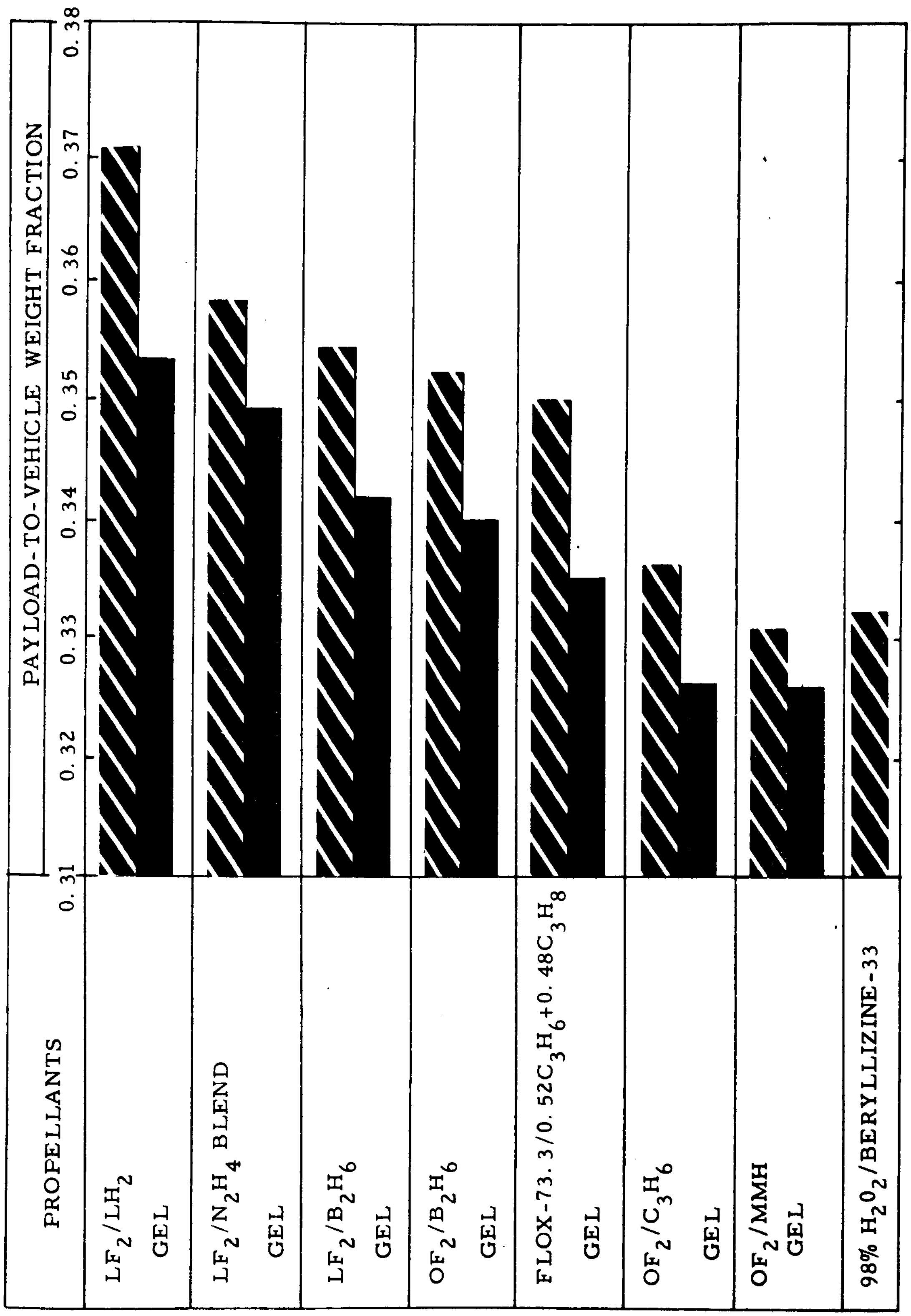


Equilibrium Temperature in Earth Space, Single Surface Material



Equilibrium Temperature in Mars Space, Single Surface Material

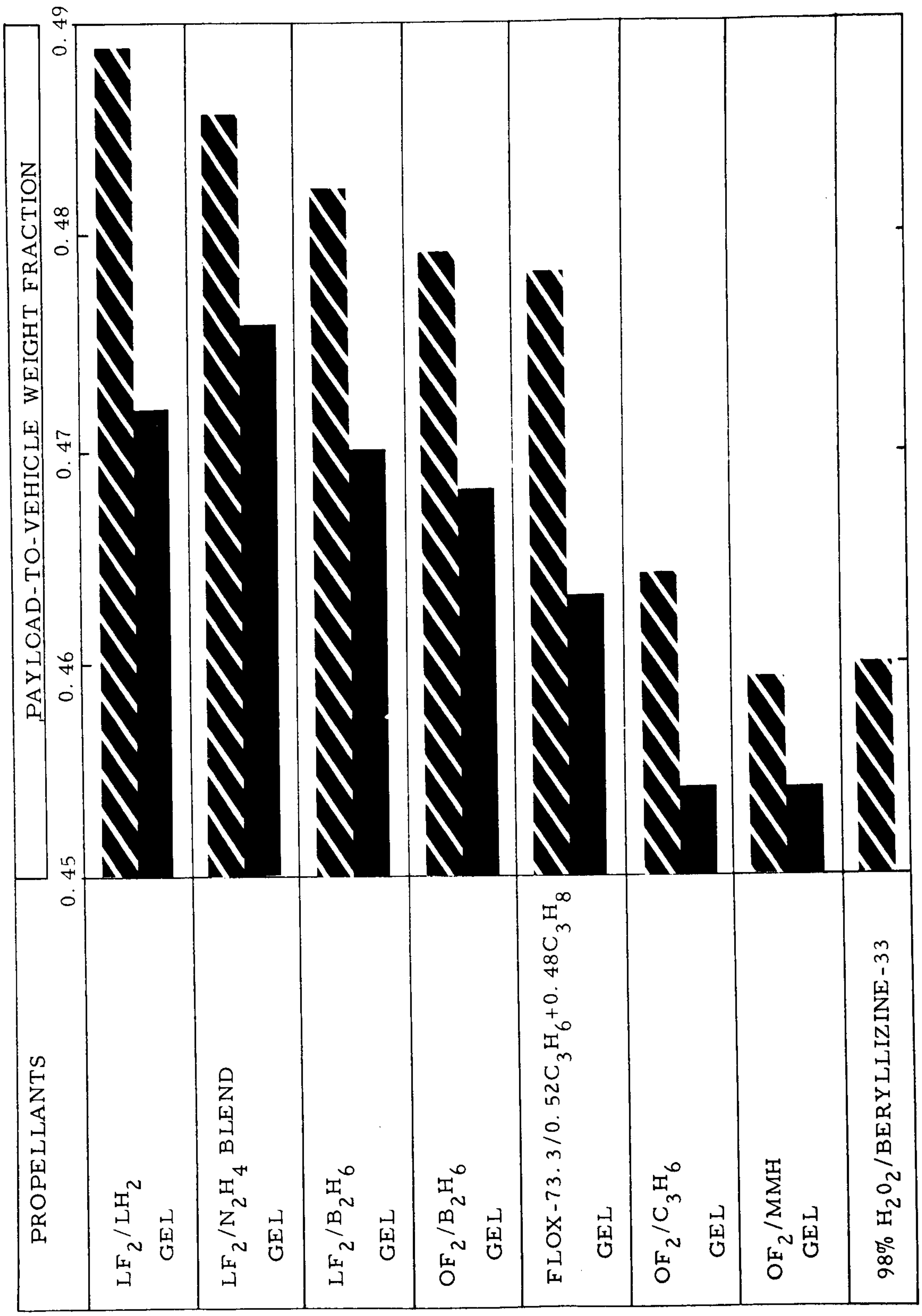
Figure 4



NOTE: ASSUMES NO PROPELLANT BOILOFF PRIOR TO USE

Lunar Descent Mission Payload Capabilities

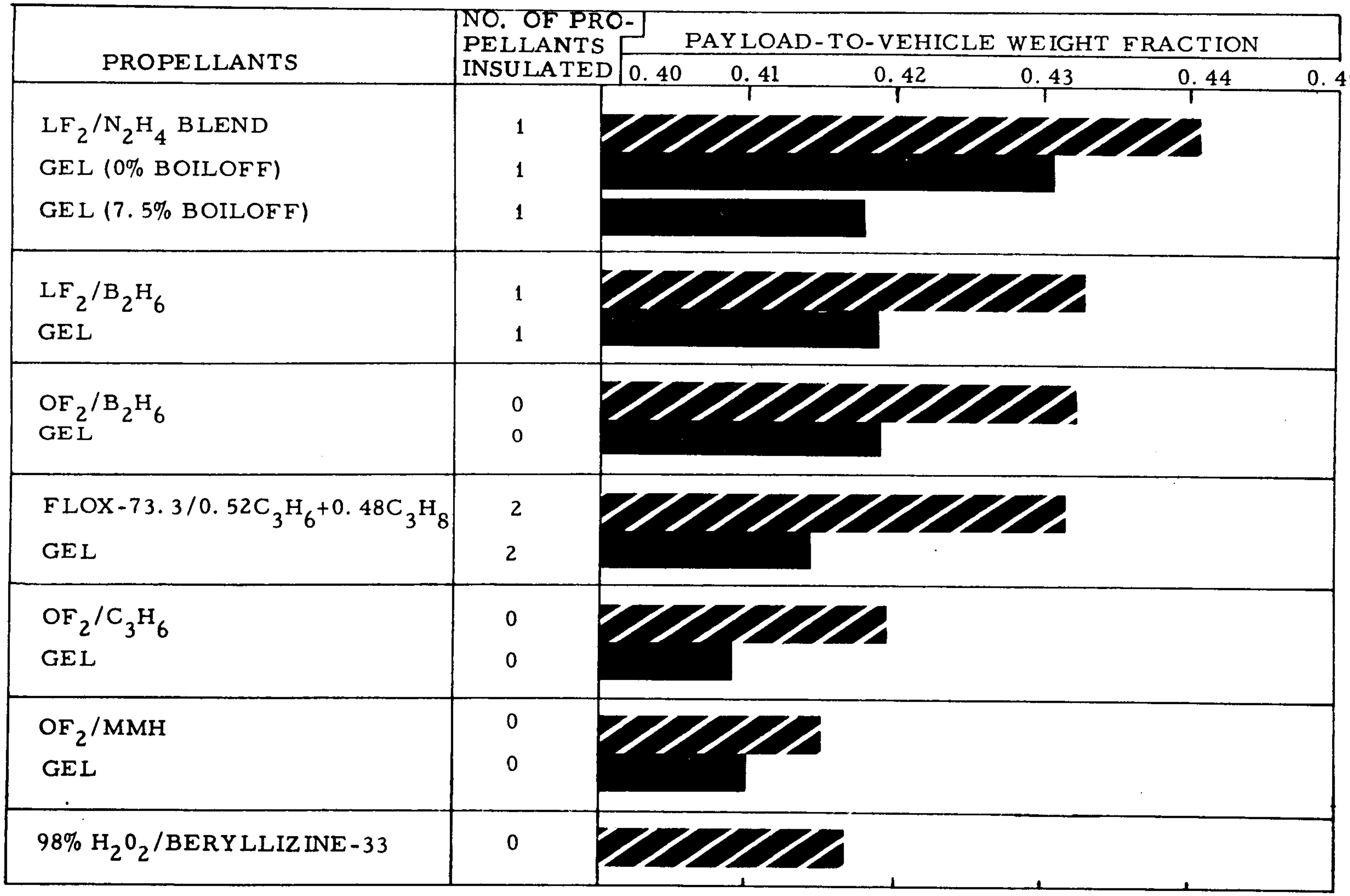
Figure 5



NOTE: ASSUMES NO PROPELLANT BOILOFF PRIOR TO USE

Lunar Ascent Mission Payload Capabilities

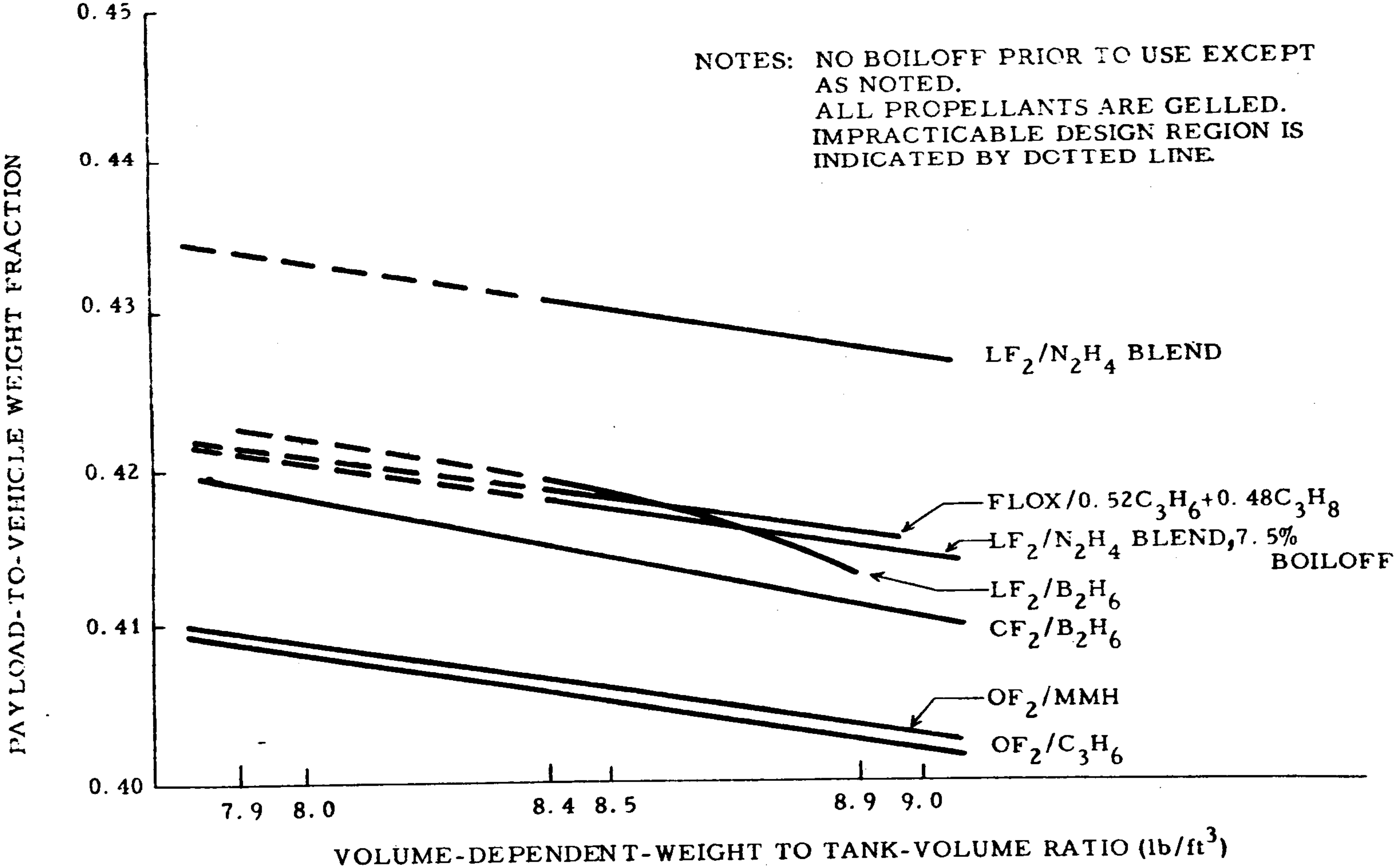
Figure 6



NOTE: ASSUMES NO PROPELLANT BOILOFF PRIOR TO USE, EXCEPT AS NOTED

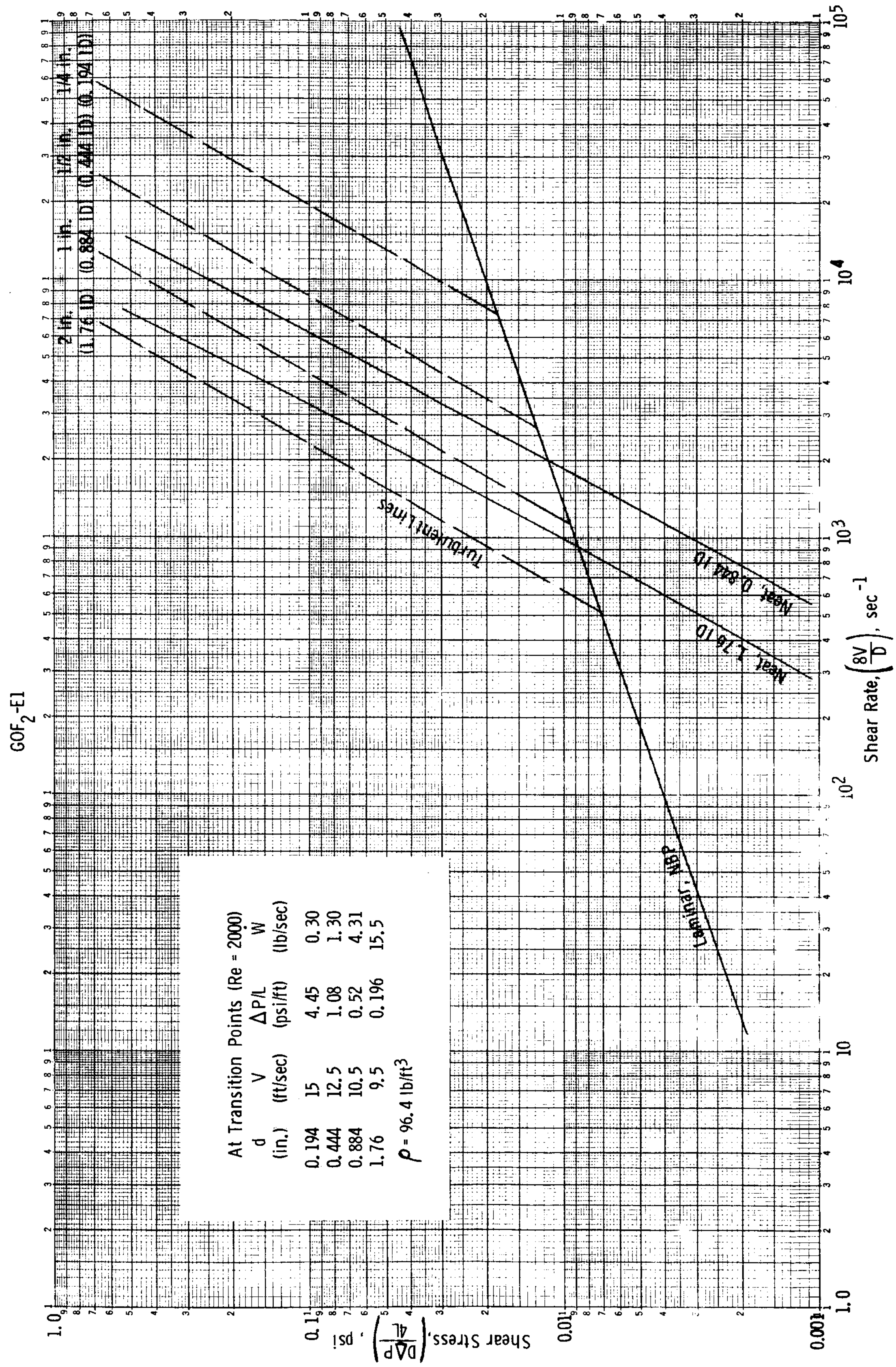
Space Probe Mission Payload Capabilities

Figure 7



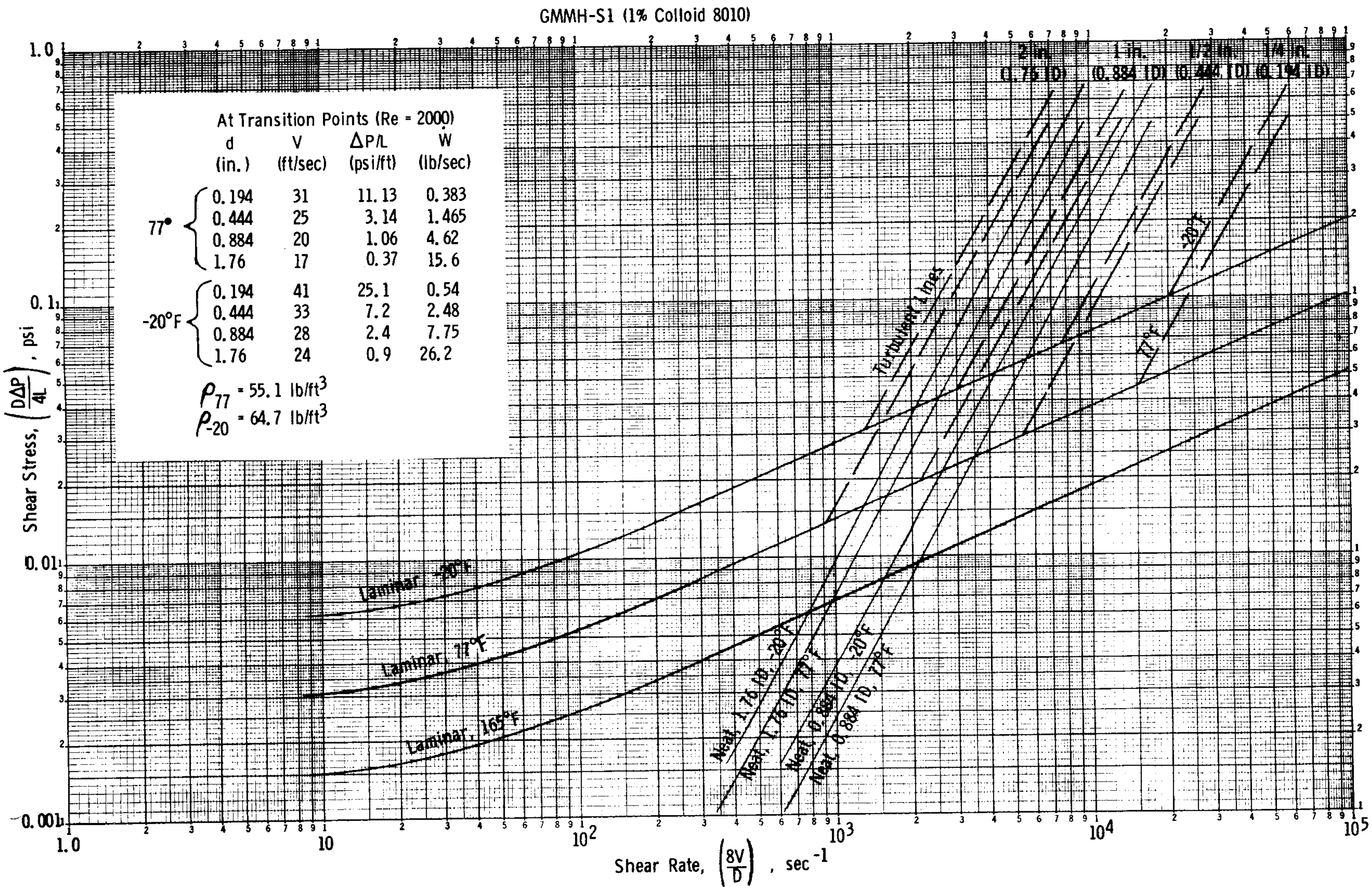
Insulation Effect on Payload Capability, Space Probe Mission

Figure 8



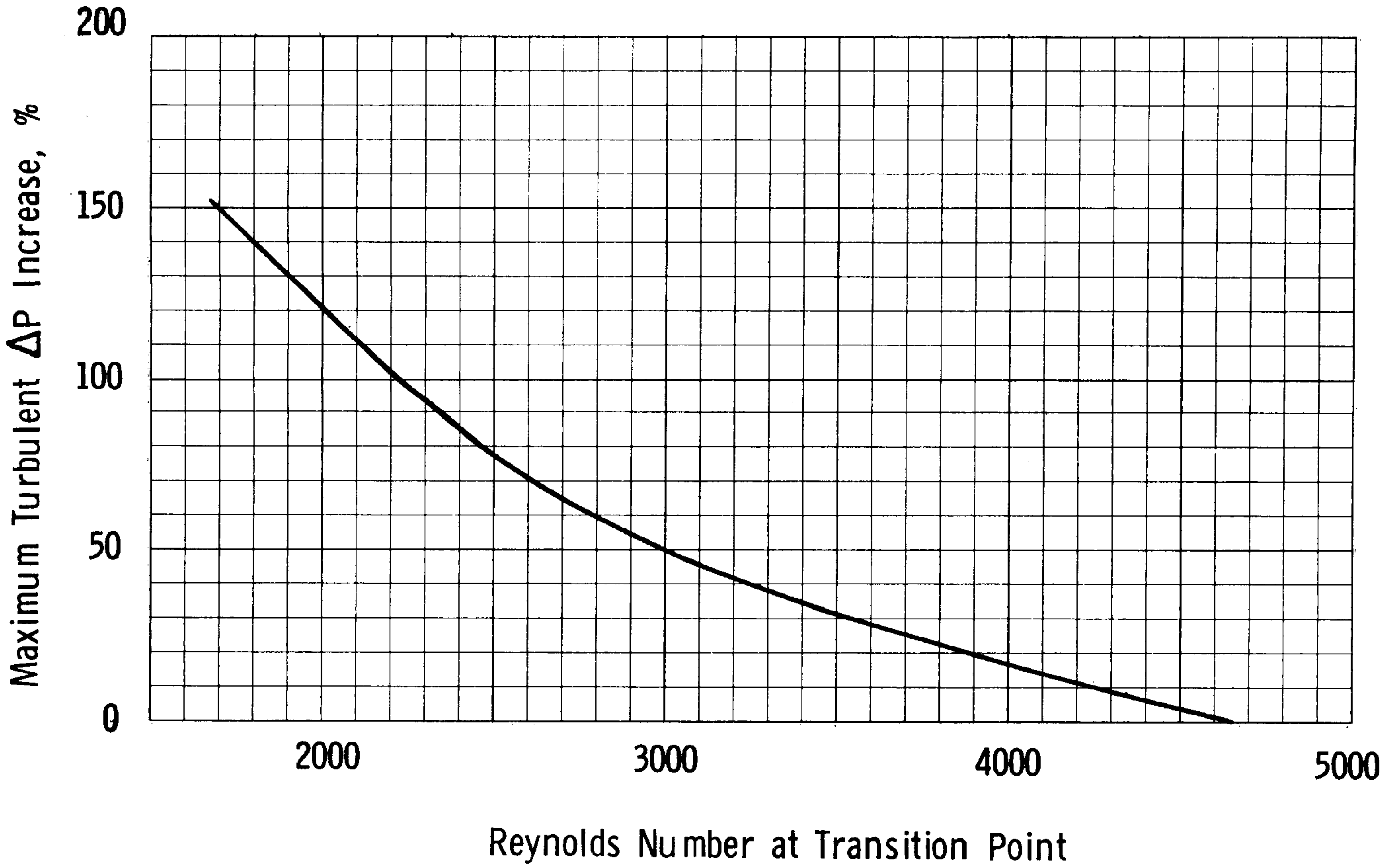
ow Curve f r GO -E1 or GO'

Figure 9



Flow Curve for GMMH-S1

Figure 10



Relative Pressure Drop vs Reynolds Number

Figure 11

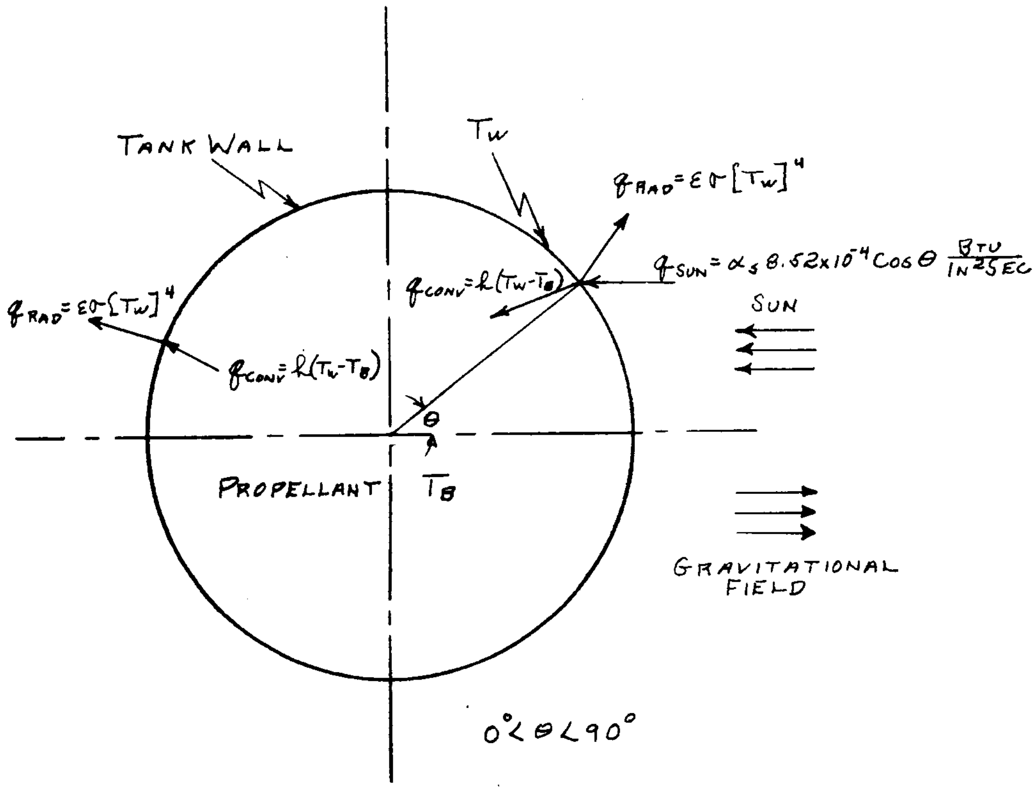


Figure 12. Neat MMH Thermal Model

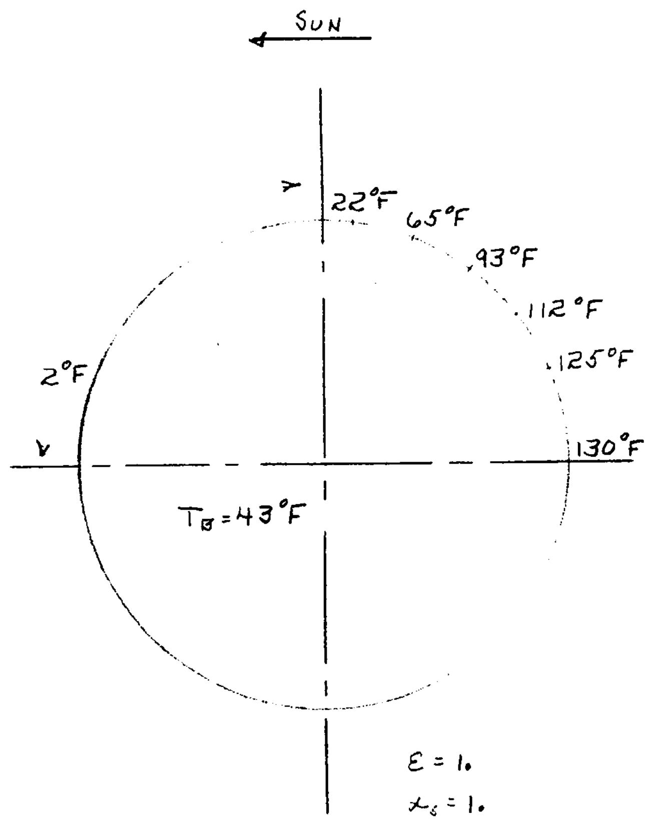
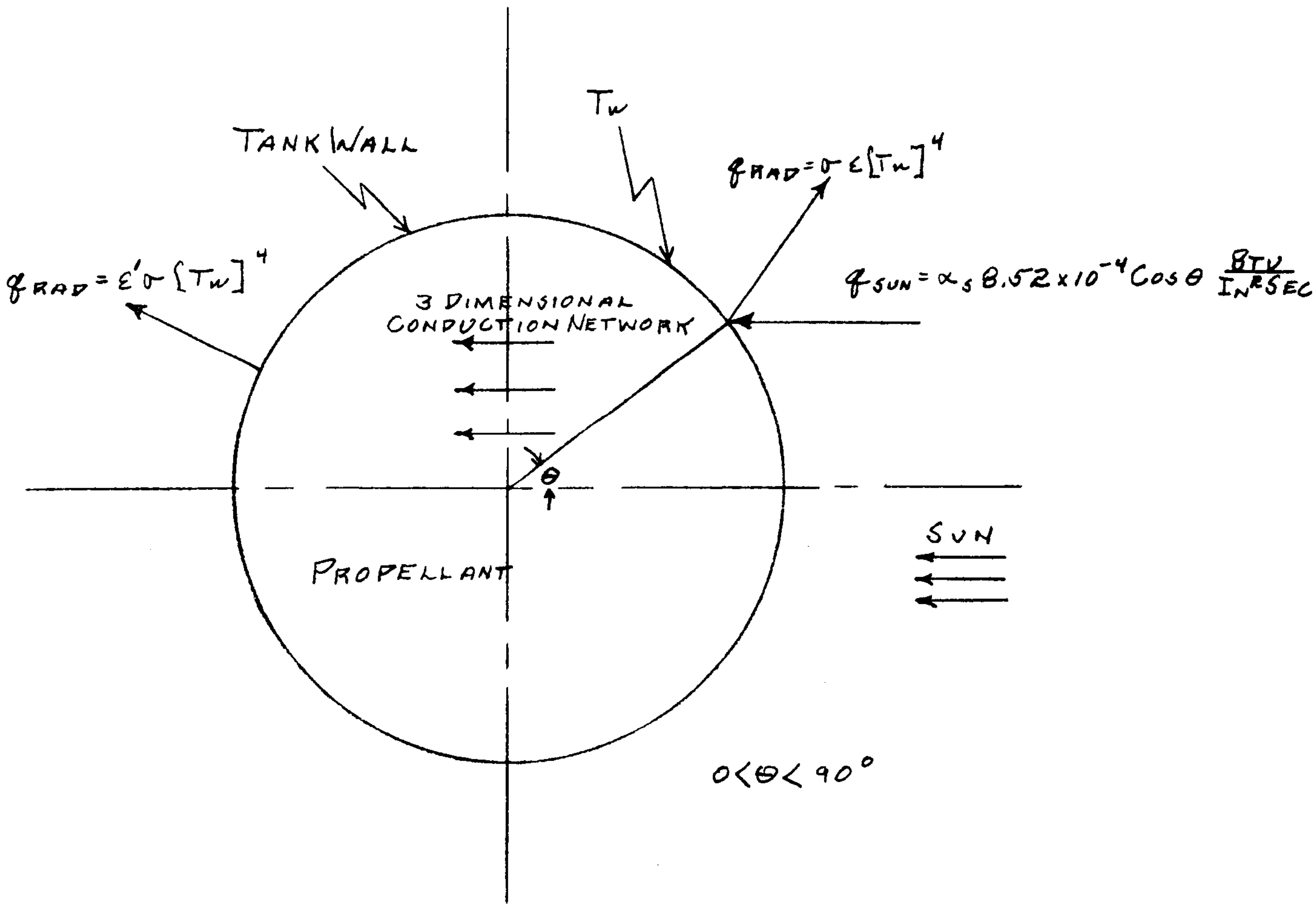


Figure 13. Tank Wall and Neat MMH Bulk Temperatures

Figure 12 and Figure 13



Gelled MMH Thermal Model

Figure 14

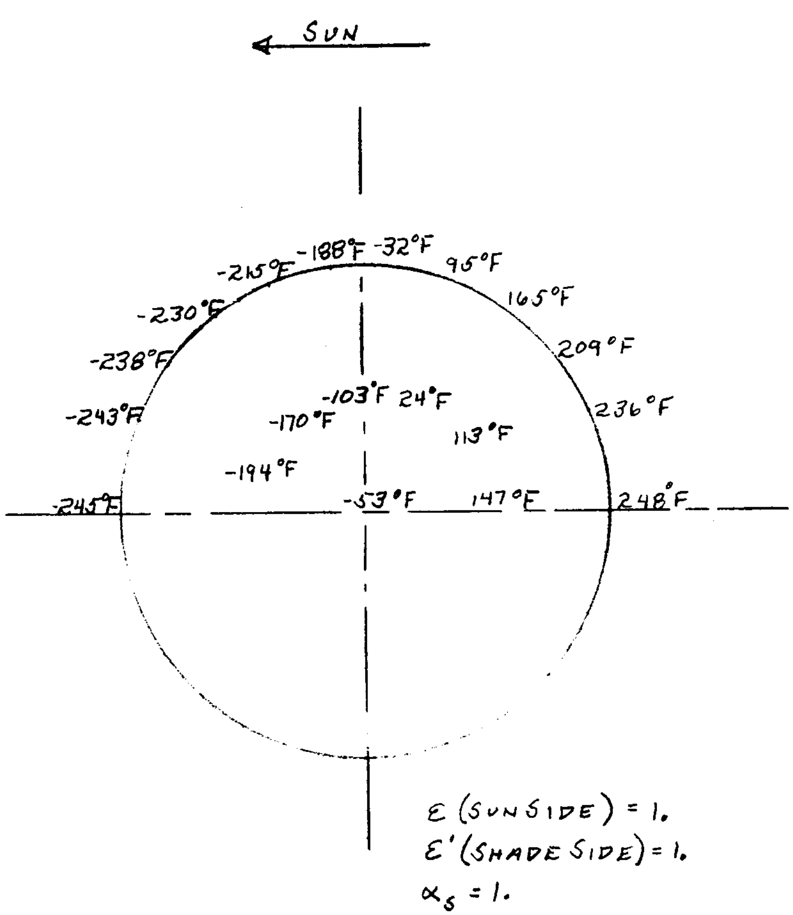


Figure 15. Gelled MMH Temperatures (α_s = 1.0)

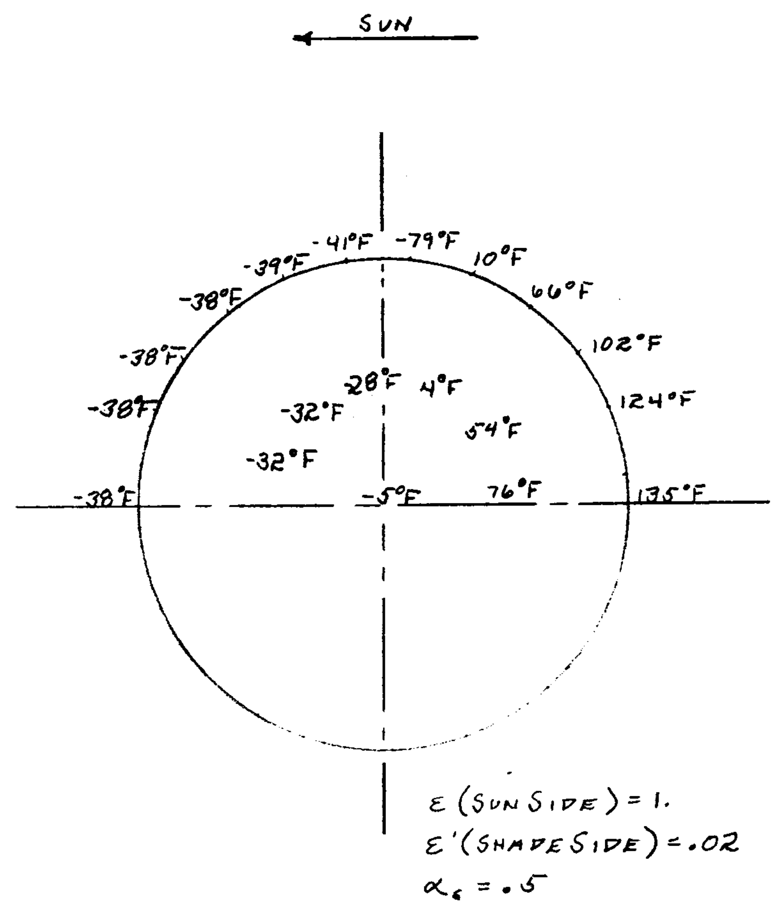
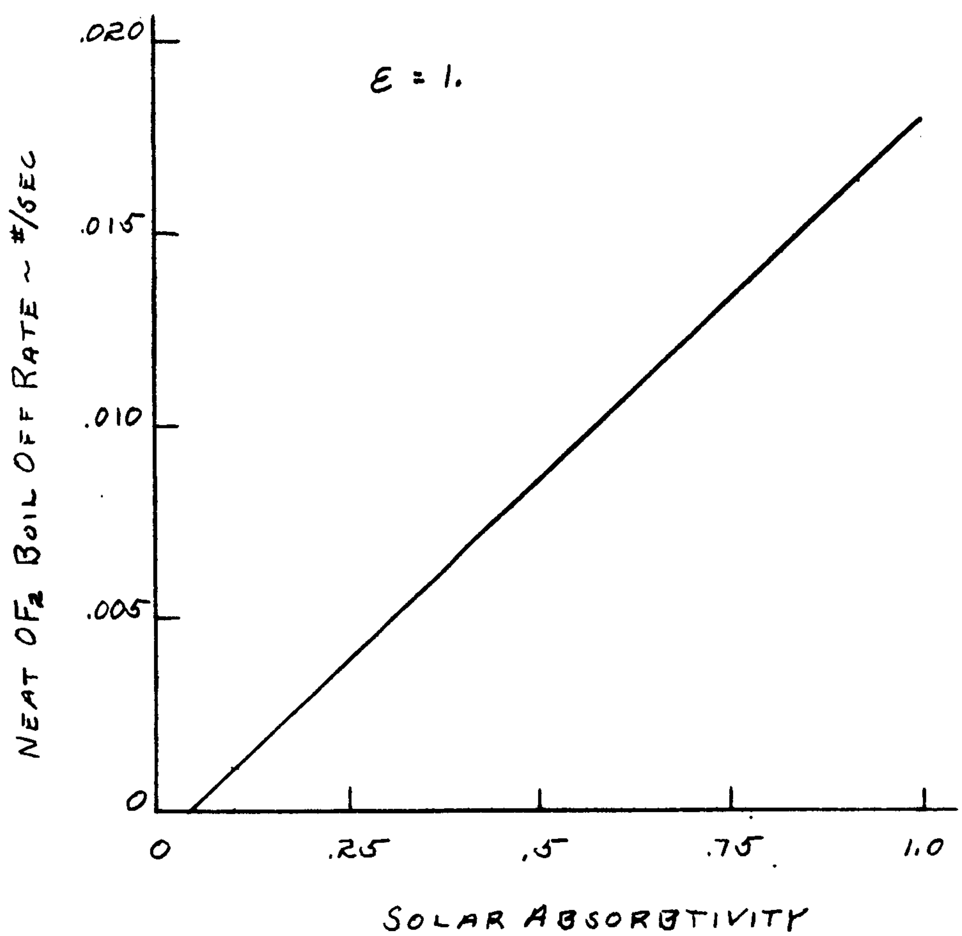


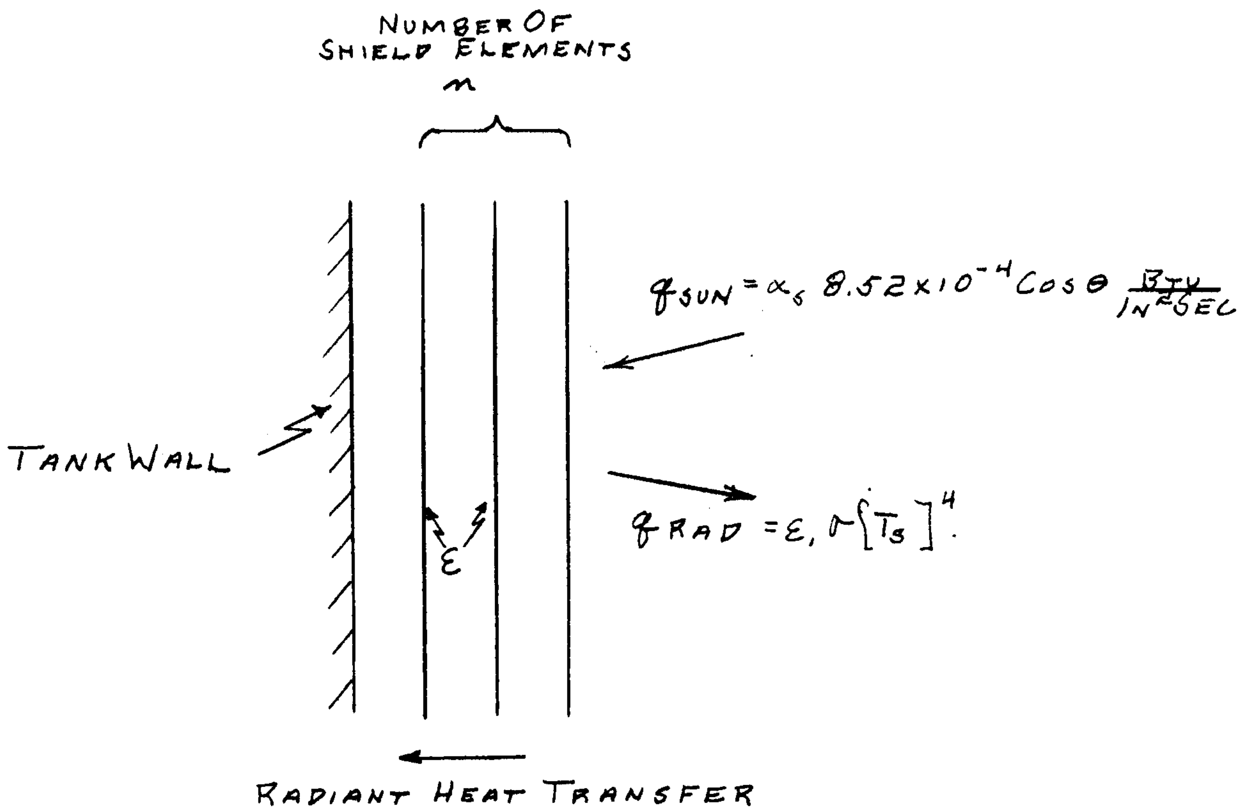
Figure 16. Gelled MMH Temperatures (α_s = 0.5)

Figure 15 and Figure 16



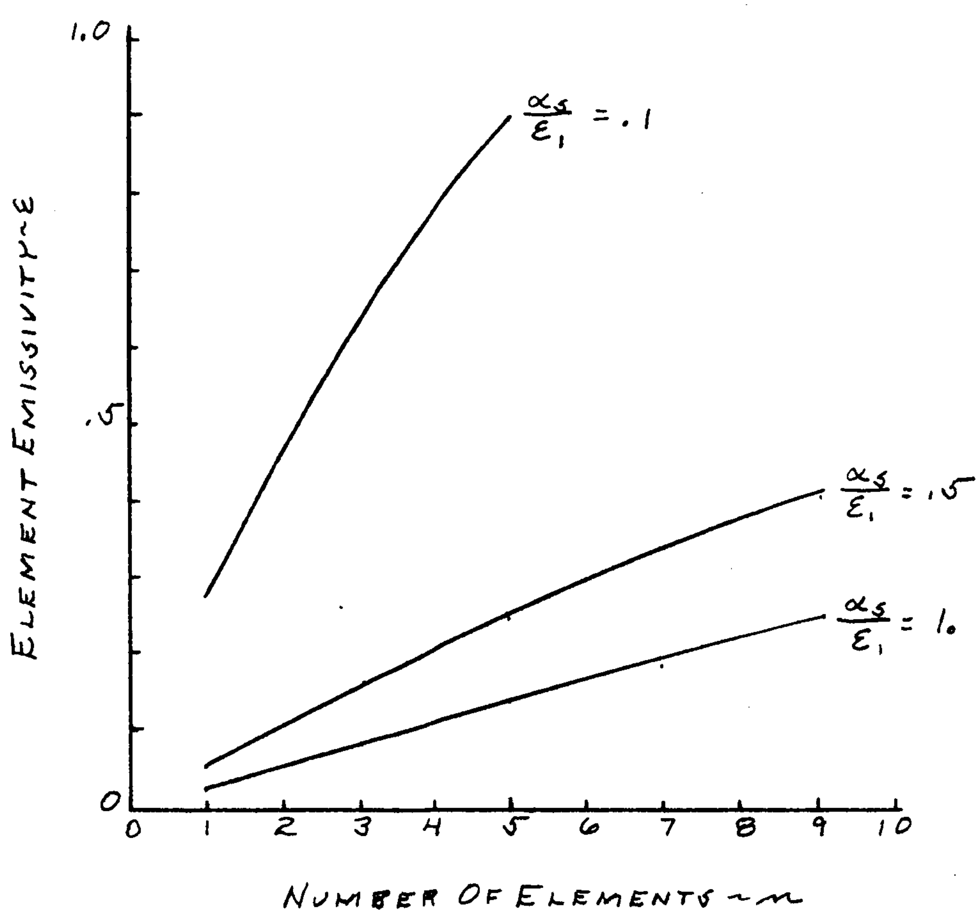
Neat OF_2 Boil-Off as a Function of Solar Absorbtivity

Figure 17



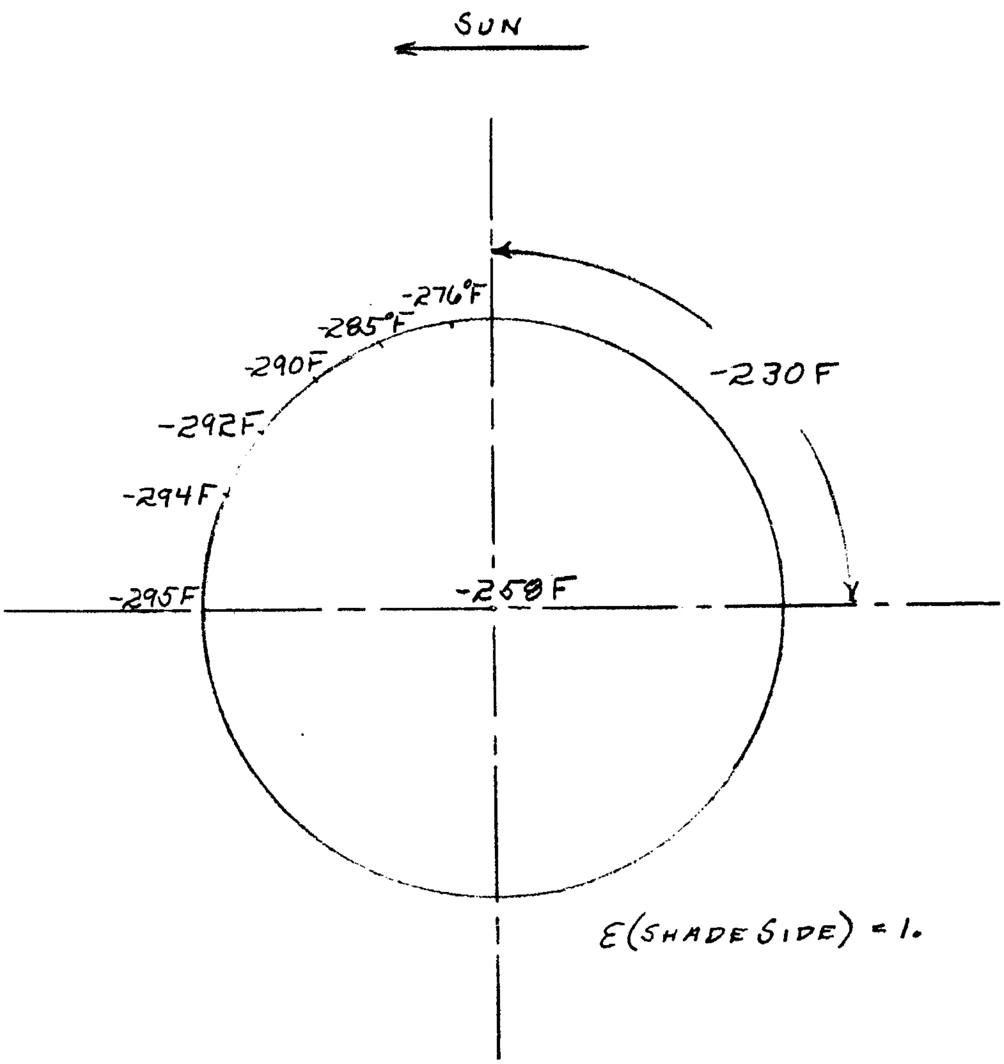
Thermal Model of Radiation Shield

Figure 18



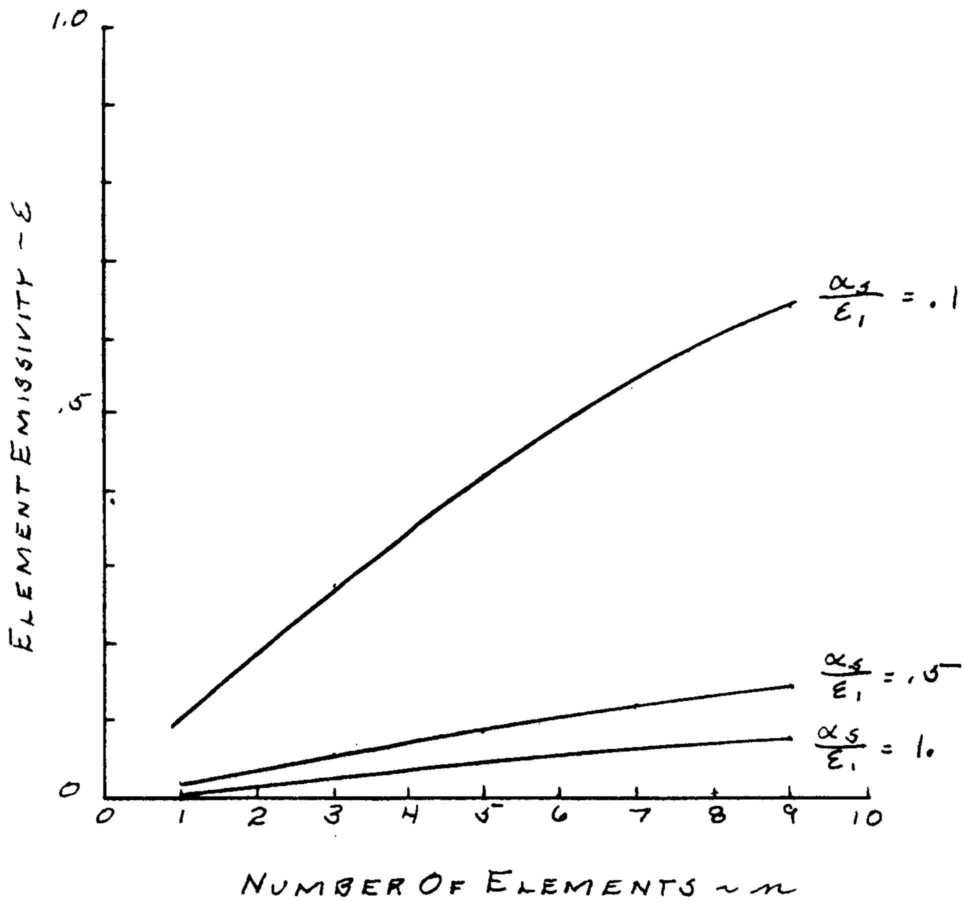
Required Heat Shield Emissivity as a Function of Number of Elements to Prevent Boil-Off of Neat OF_2

Figure 19



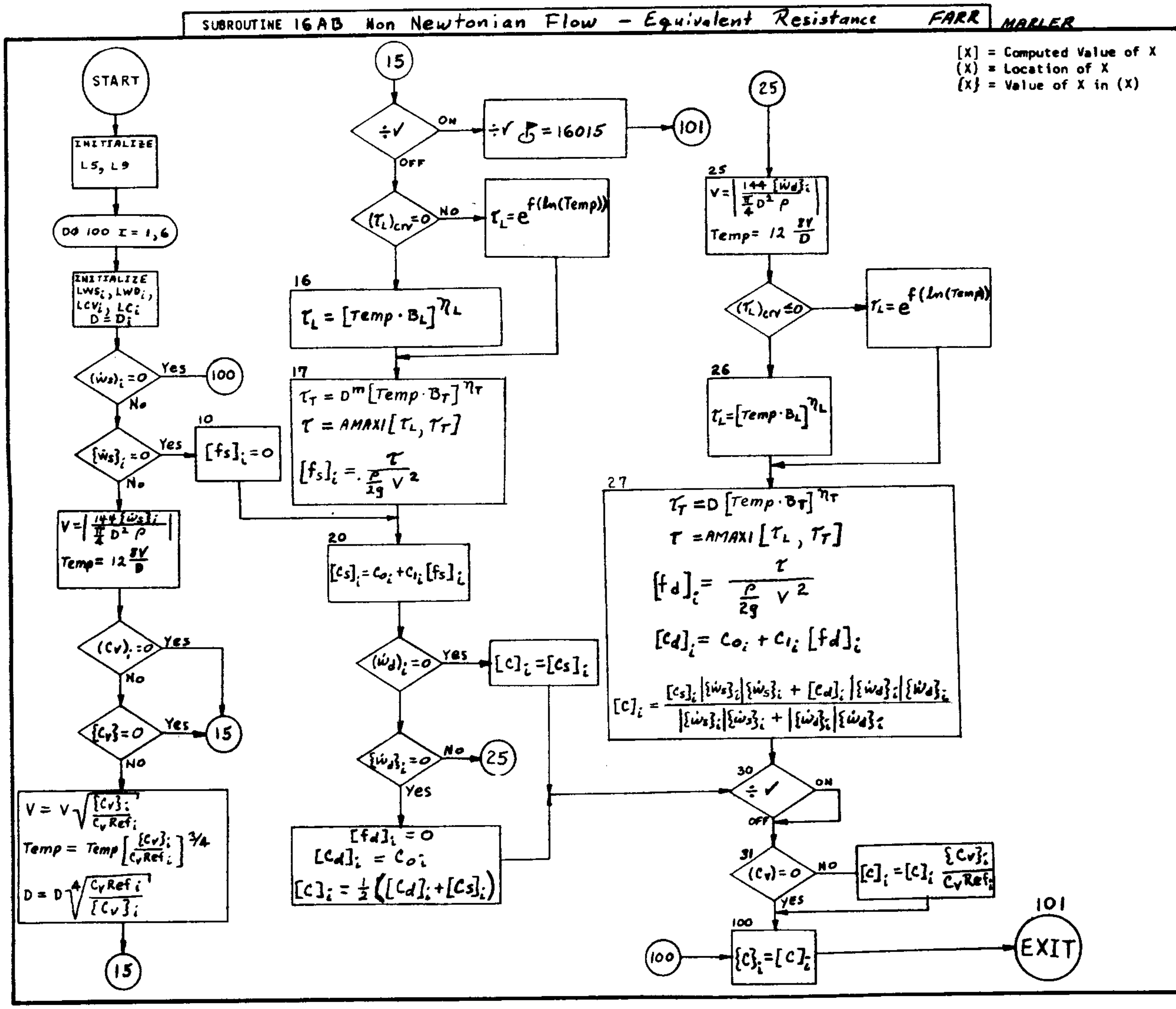
Gelled OF_2 Temperatures

Figure 20



Required Heat Shield Emissivity as a Function of Number of Elements to Prevent Boil-Off of Gelled OF_2

Figure 21



SR 16 AB

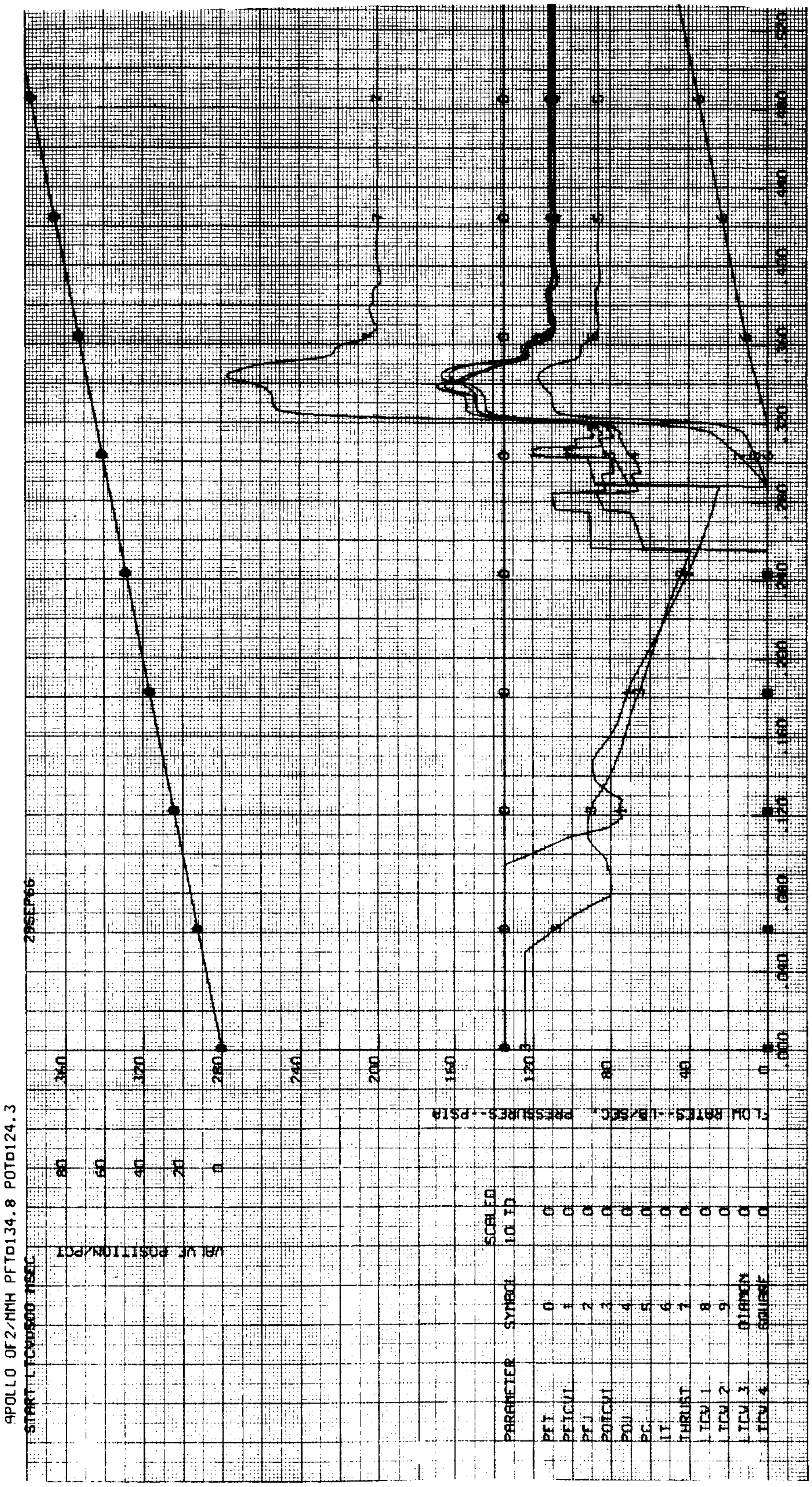
DATE: 10/6/66

NO.	PARAMETER	UNITS	NO.	PARAMETER	UNITS
2	SR. NO.		51	C_v Ref. 3	
3	REENT	P	52	$[f_s]$ 3	
4	(REENT)		53	$[C_s]$ 3	
5	(ρ)		54	$[f_d]$ 3	
6	BYP. ENT		55	$[C_d]$ 3	
7			56	$[C]$ 3	
8			57		
9	(τ_L)	crv	58	$(\dot{W}_s)$ 4	
10	B_L		59	$(\dot{W}_d)$ 4	
11	η_L		60	(C_v) 4	
12	B_T		61	(C) 4	STORE
13	η_T		62	D 4	
14	m		63	C_o 4	
15			64	C_1 4	
16	$(\dot{W}_s)$ 1		65	C_v Ref. 4	
17	$(\dot{W}_d)$ 1		66	$[f_s]$ 4	
18	(C_v) 1		67	$[C_s]$ 4	
19	(C) 1	STORE	68	$[f_d]$ 4	
20	D 1		69	$[C_d]$ 4	
21	C_o 1		70	$[C]$ 4	
22	C_1 1		71		
23	C_vRef 1		72	$(\dot{W}_s)$ 5	
24	$[f_s]$ 1		73	$(\dot{W}_d)$ 5	
25	$[C_s]$ 1		74	(C_v) 5	
26	$[f_D]$ 1		75	(C) 5	Store
27	$[C_D]$ 1		76	D 5	
28	$[C]$ 1		77	C_o 5	
29			78	C_1 5	
30	$(\dot{W}_s)$ 2		79	C_v Ref 5	
31	$(\dot{W}_d)$ 2		80	$[f_s]$ 5	
32	(C_v) 2		81	$[C_s]$ 5	
33	(C) 2	Store	82	$[f_d]$ 5	
34	D 2		83	$[C_d]$ 5	
35	C_o 2		84	$[C]$ 5	
36	C_1 2		85		
37	C_v Ref 2		86	$(\dot{W}_s)$ 6	
38	$[f_s]$ 2		87	$(\dot{W}_d)$ 6	
39	$[C_s]$ 2		88	(C_v) 6	
40	$[f_d]$ 2		89	(C) 6	Store
41	$[C_d]$ 2		90	D 6	
42	$[C]$ 2		91	C_o 6	
43			92	C_1 6	
44	$(\dot{W}_s)$ 3		93	C_v Ref 6	
45	$(\dot{W}_d)$ 3		94	$[f_s]$ 6	
46	(C_v) 3		95	$[C_s]$ 6	
47	(C) 3	Store	96	$[f_d]$ 6	
48	D 3		97	$[C_d]$ 6	
49	C_o 3		98	$[C]$ 6	
50	C_1 3		99		

RWL: 5-6-63

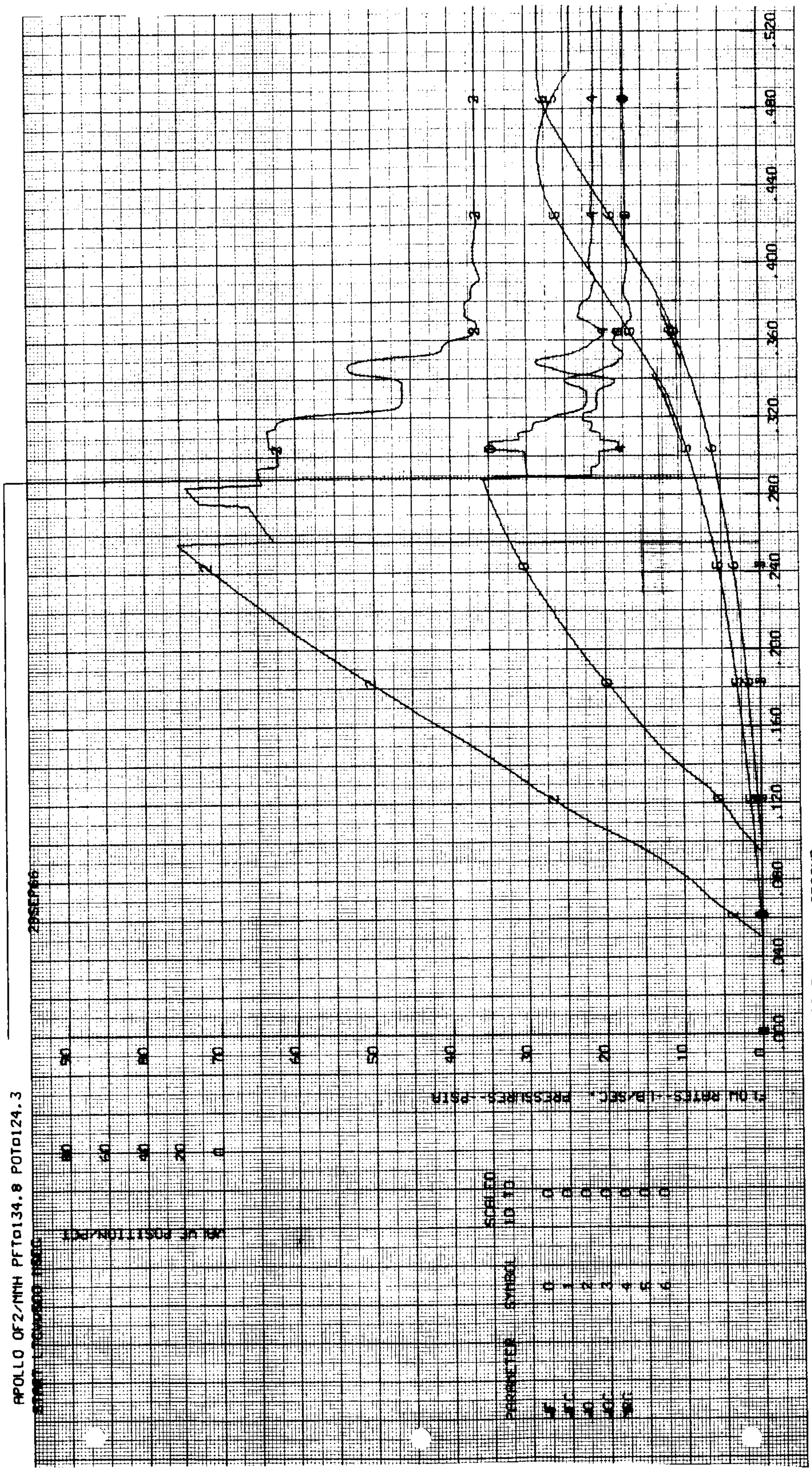
Subroutine 16AB-Non-Newtonian Flow

Figure 22



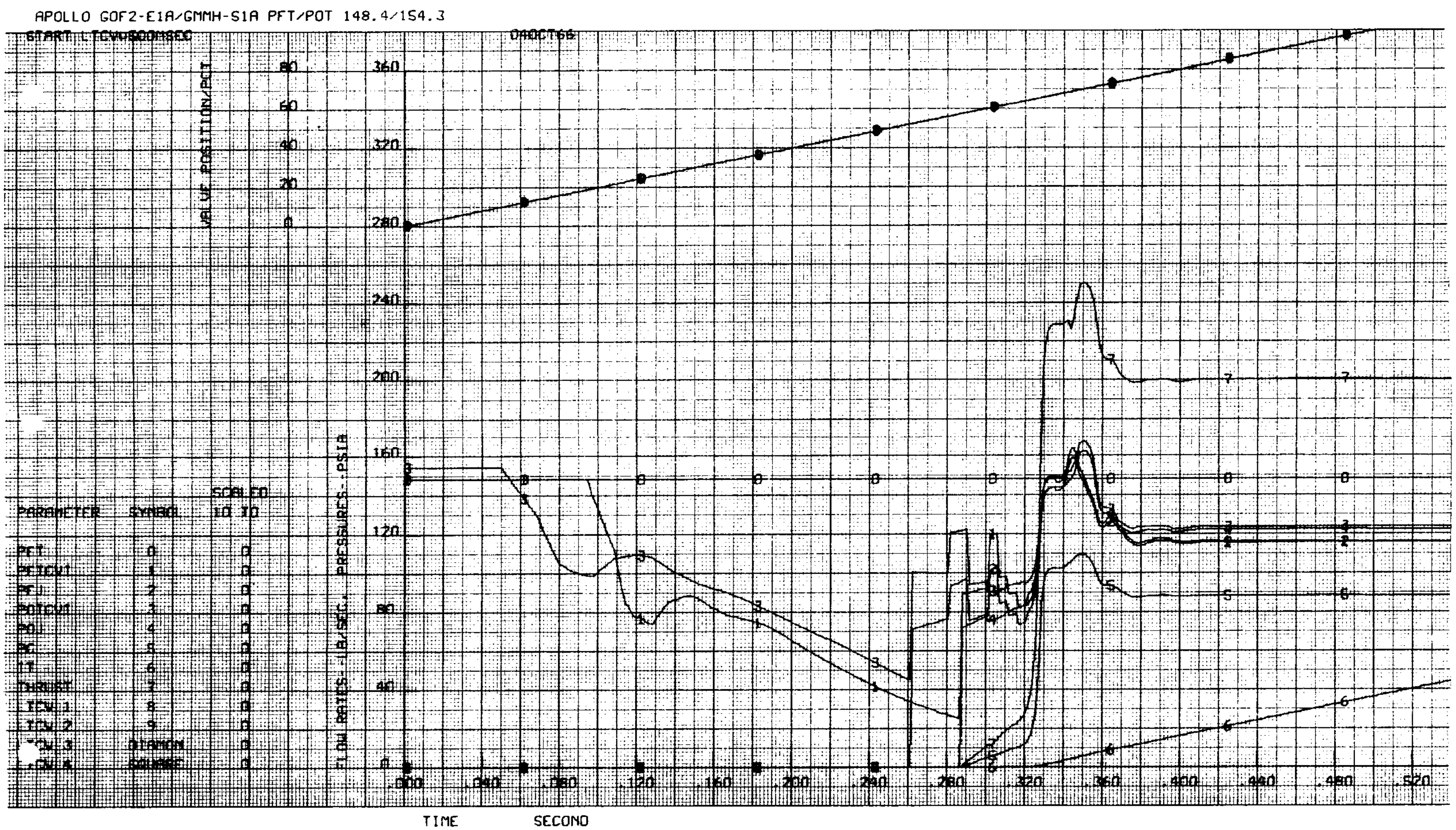
Apollo OF_2/MMH Start Transient, Part 1

Figure 23



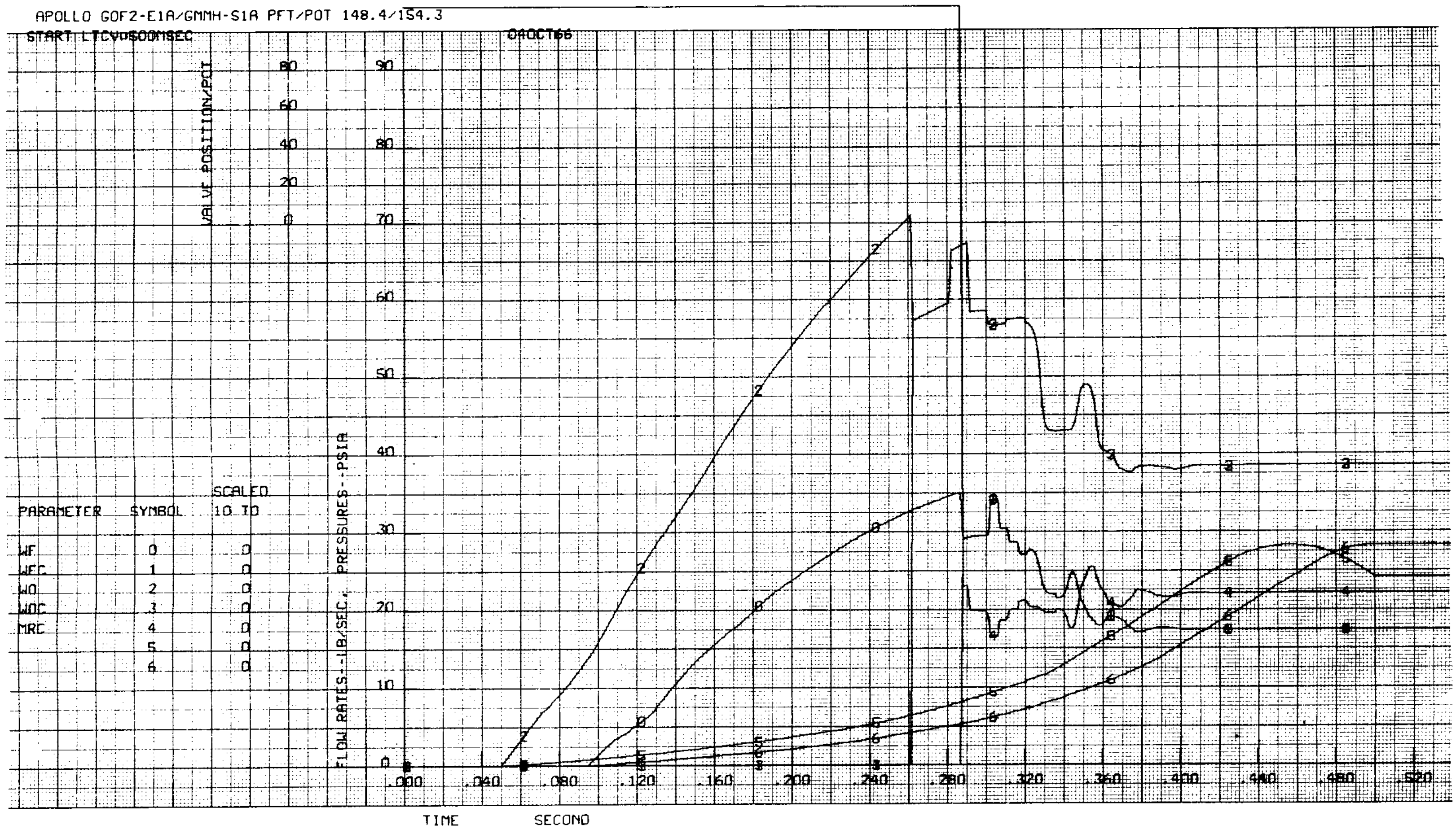
Apollo OF_2/MMH Start Transient, Part 2

Figure 24



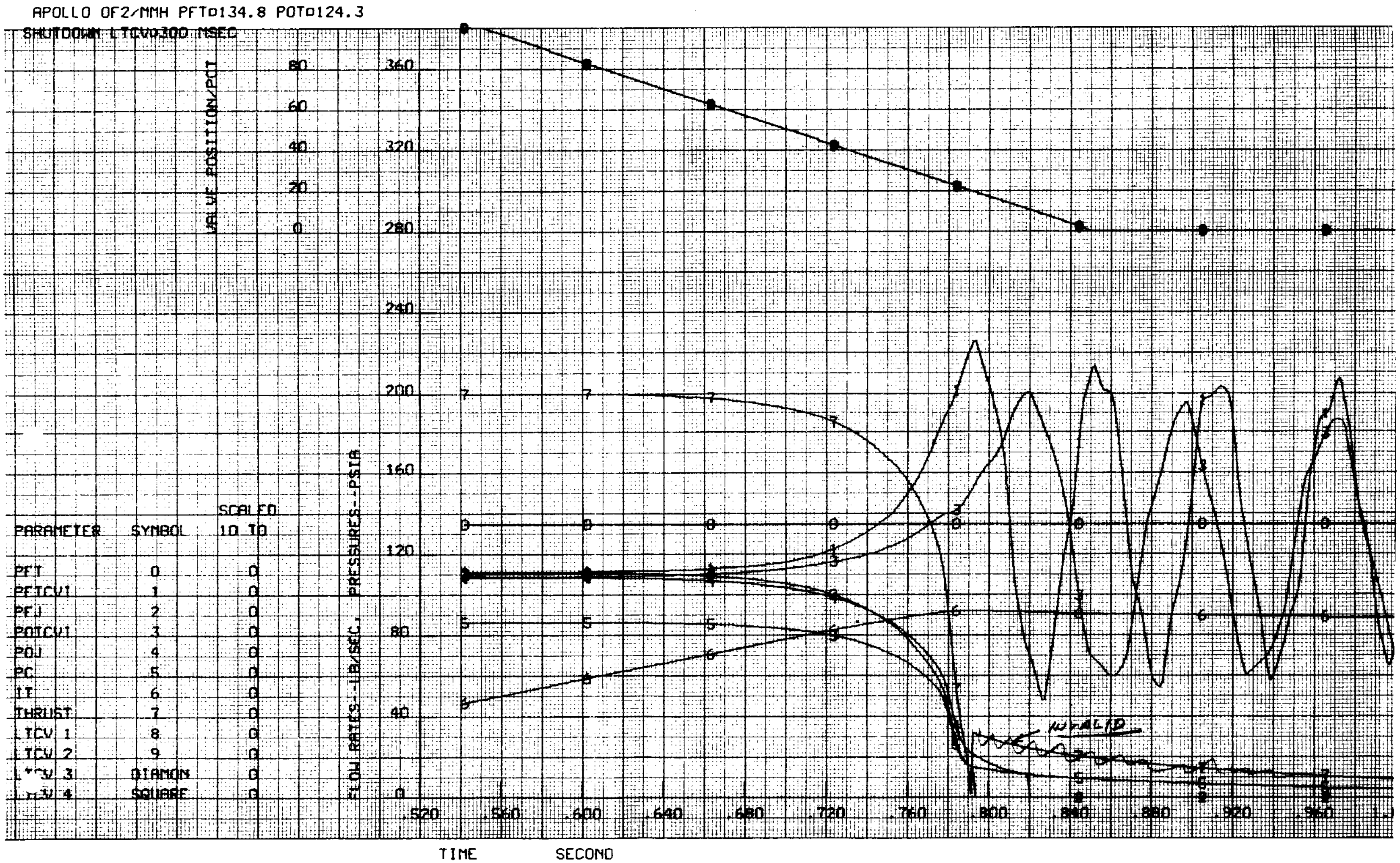
Apollo GOF_2-E1/GMMH-S1 Start Transient, Part 1

Figure 25



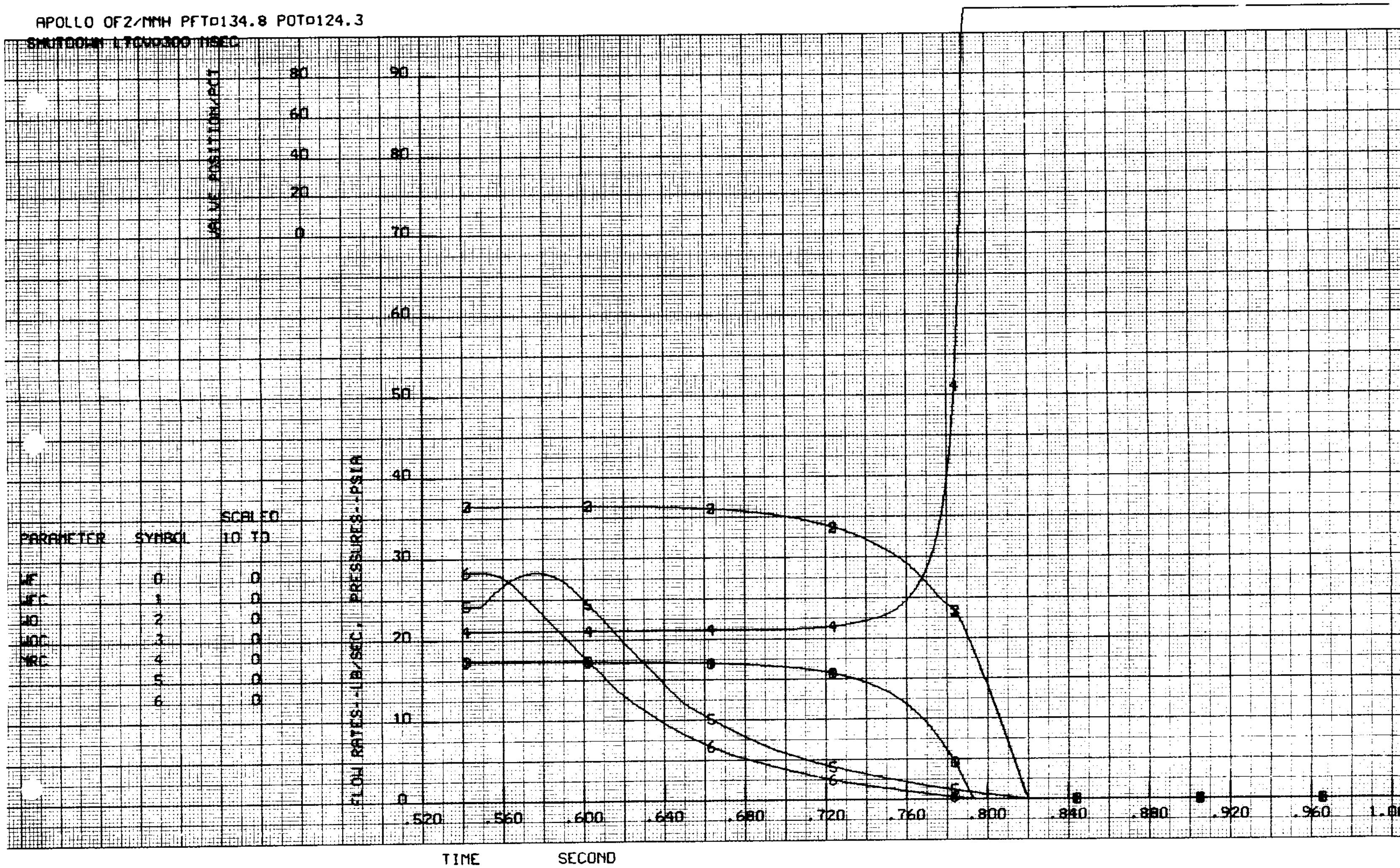
Apollo GOF_2-E1/GMMH-S1 Start Transient, Part 2

Figure 26



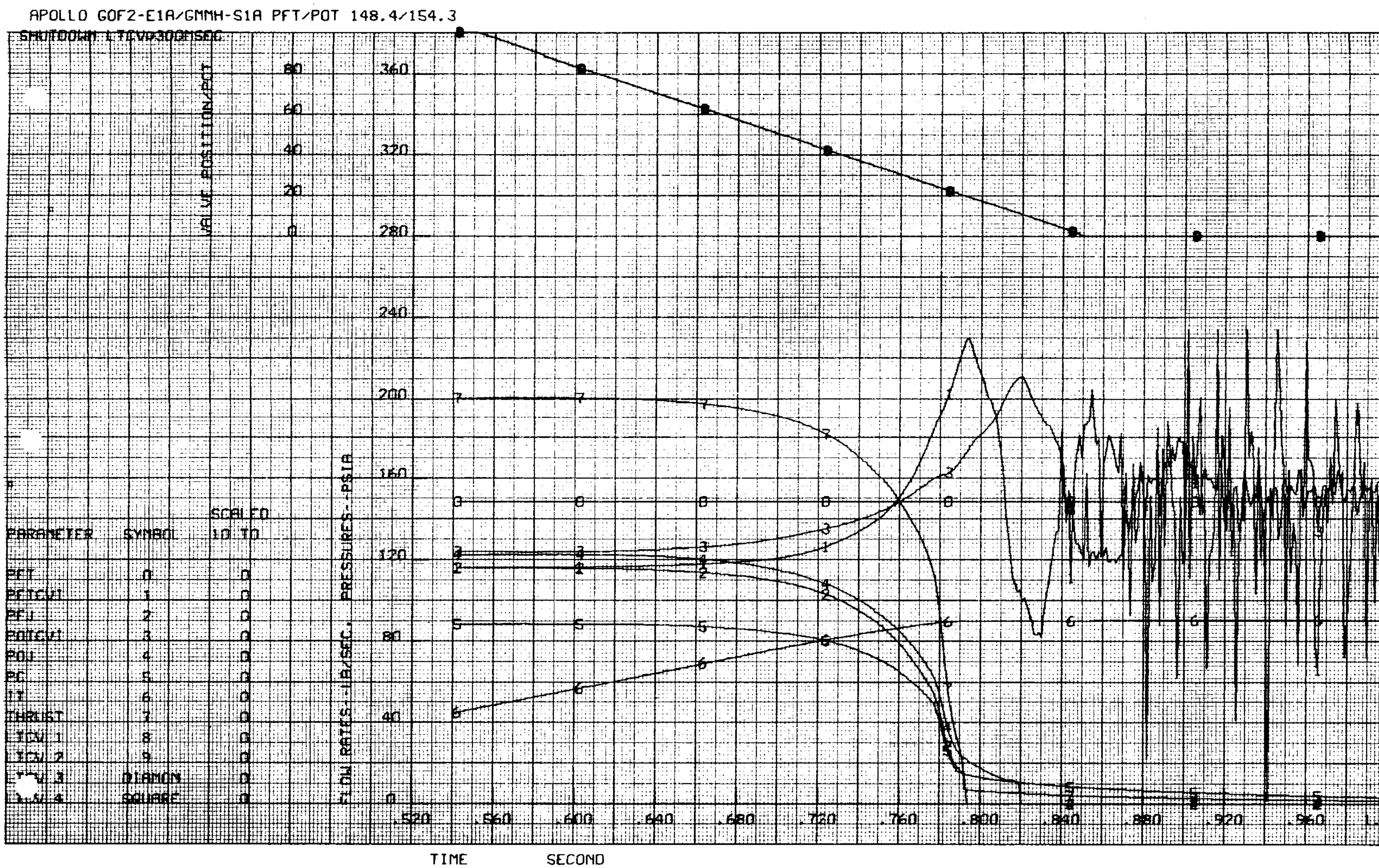
Apollo OF_2/MMH Shutdown Transient, Part 1

Figure 27



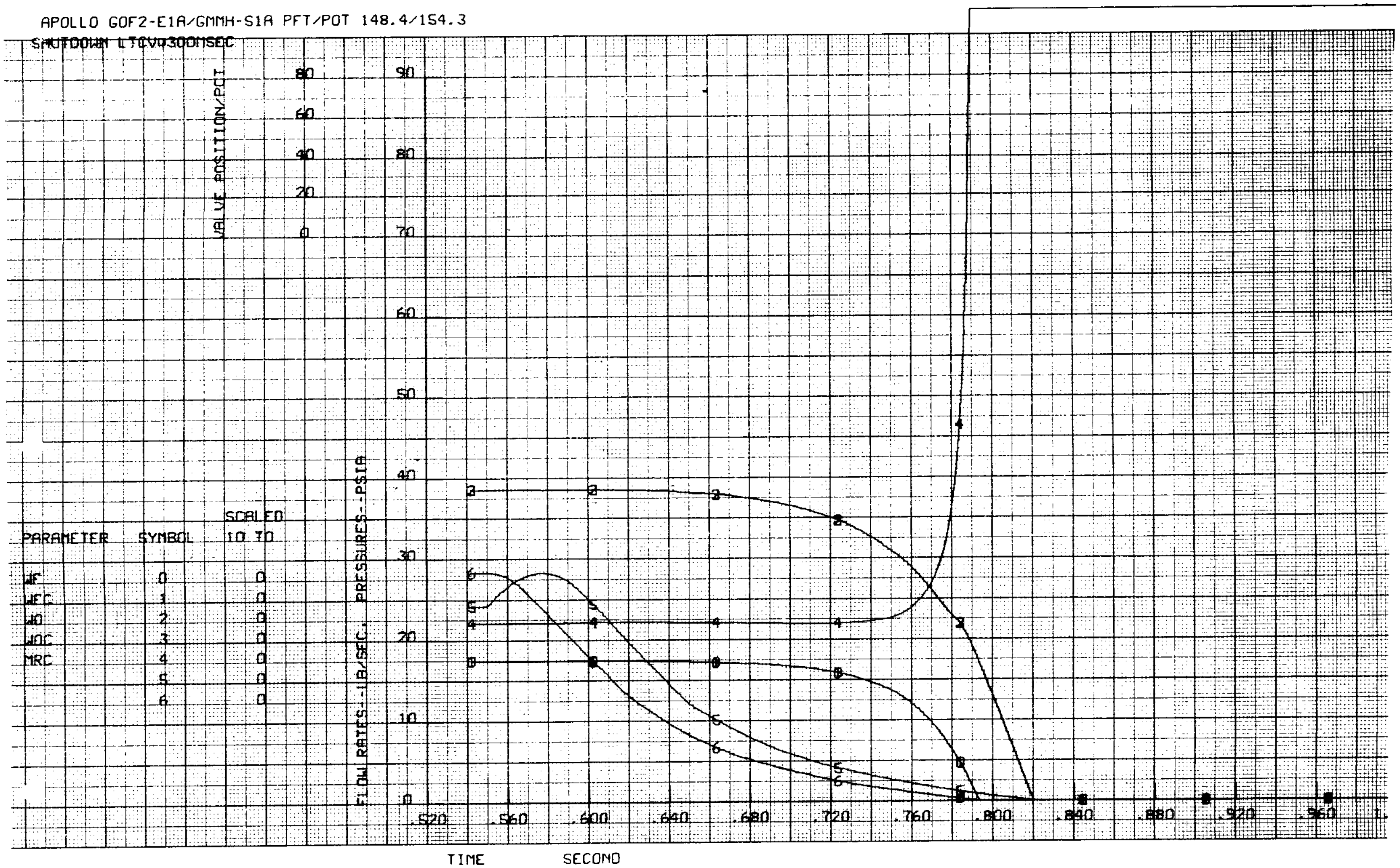
Apollo OF_2/MMH Shutdown Transient, Part 2

Figure 28



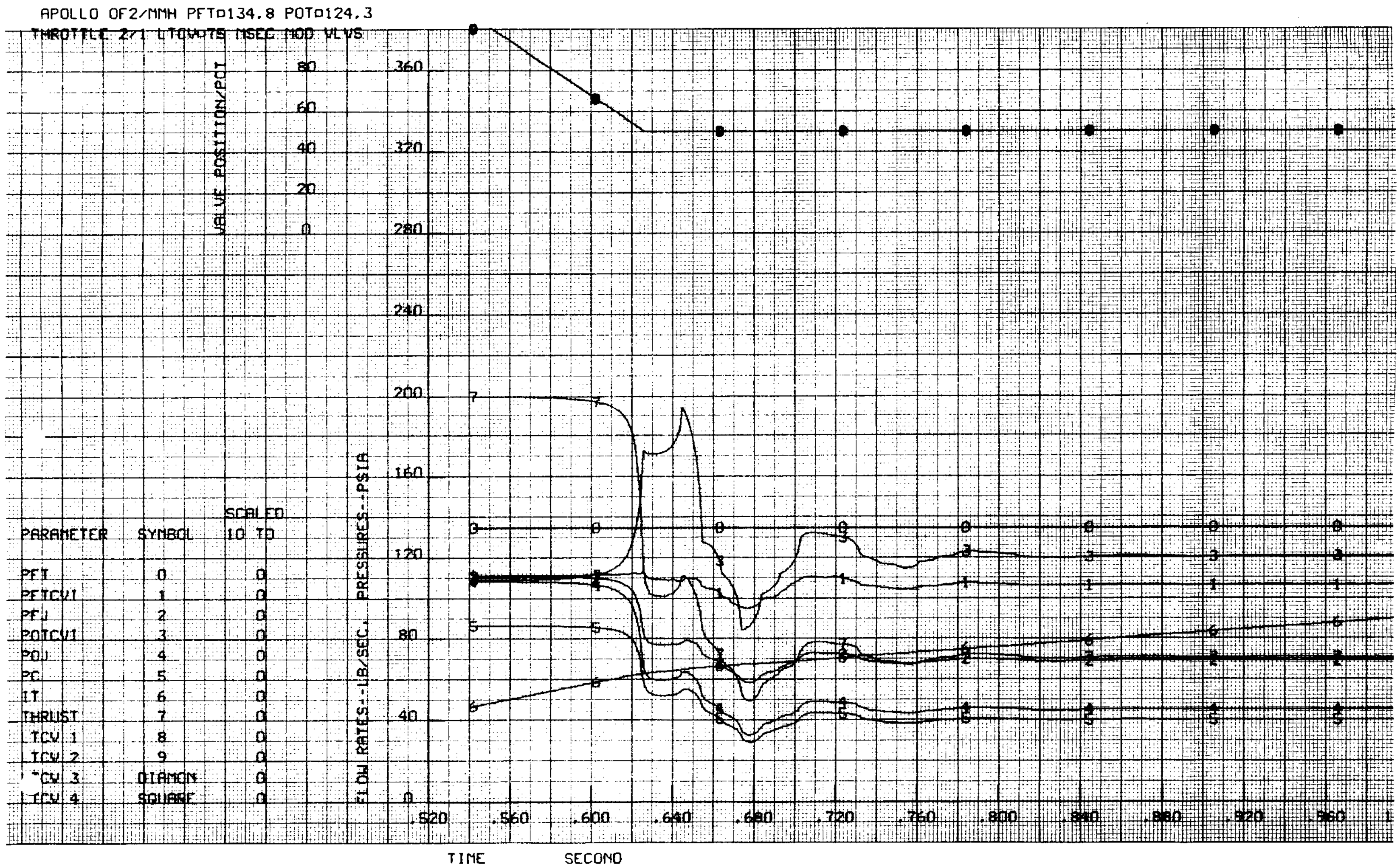
Apollo GOF_2-E1/GMMH-S1 Shutdown Transient, Part 1

Figure 29



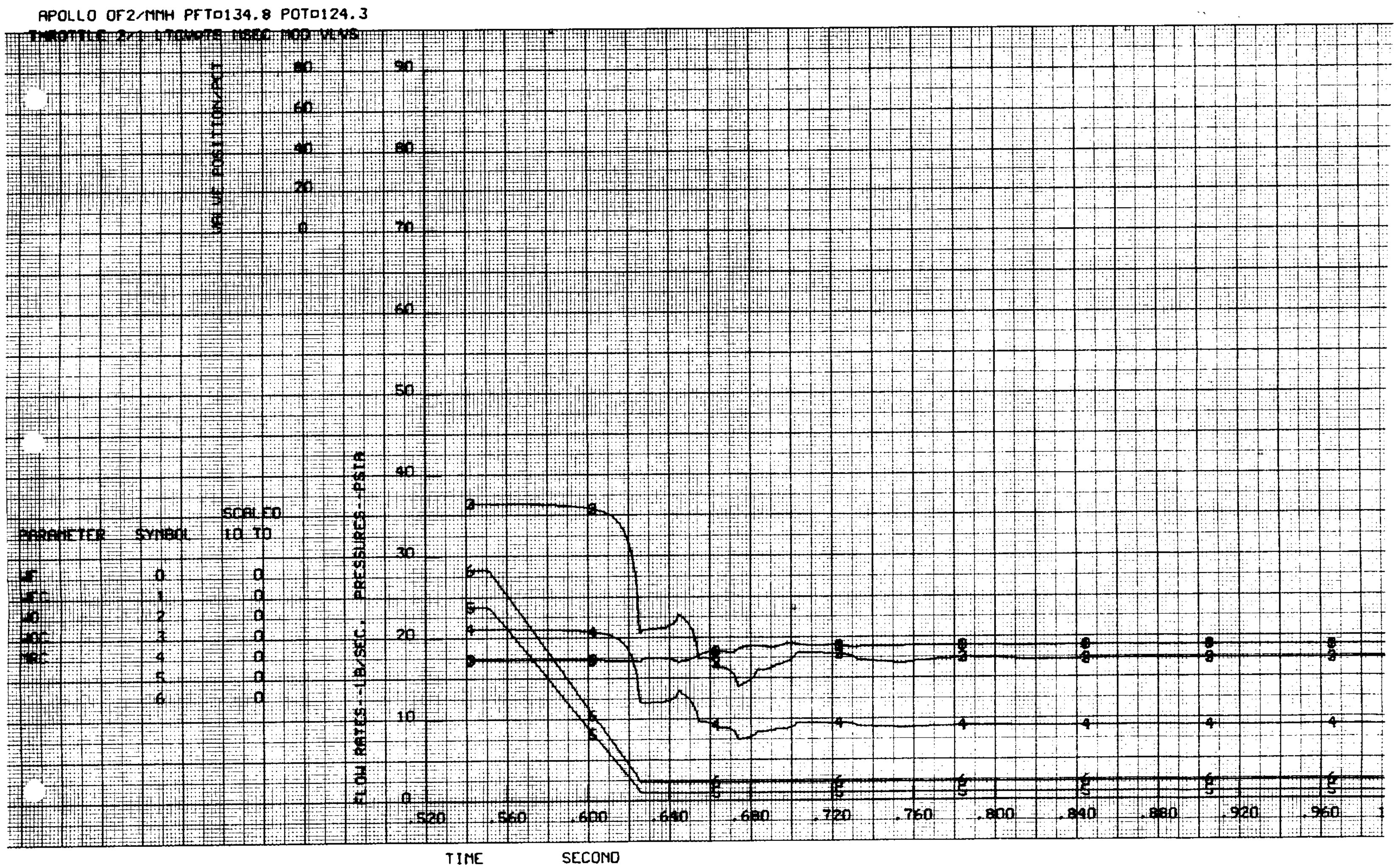
Apollo GOF_2-E1/GMMH-S1 Shutdown Transient, Part 2

Figure 30



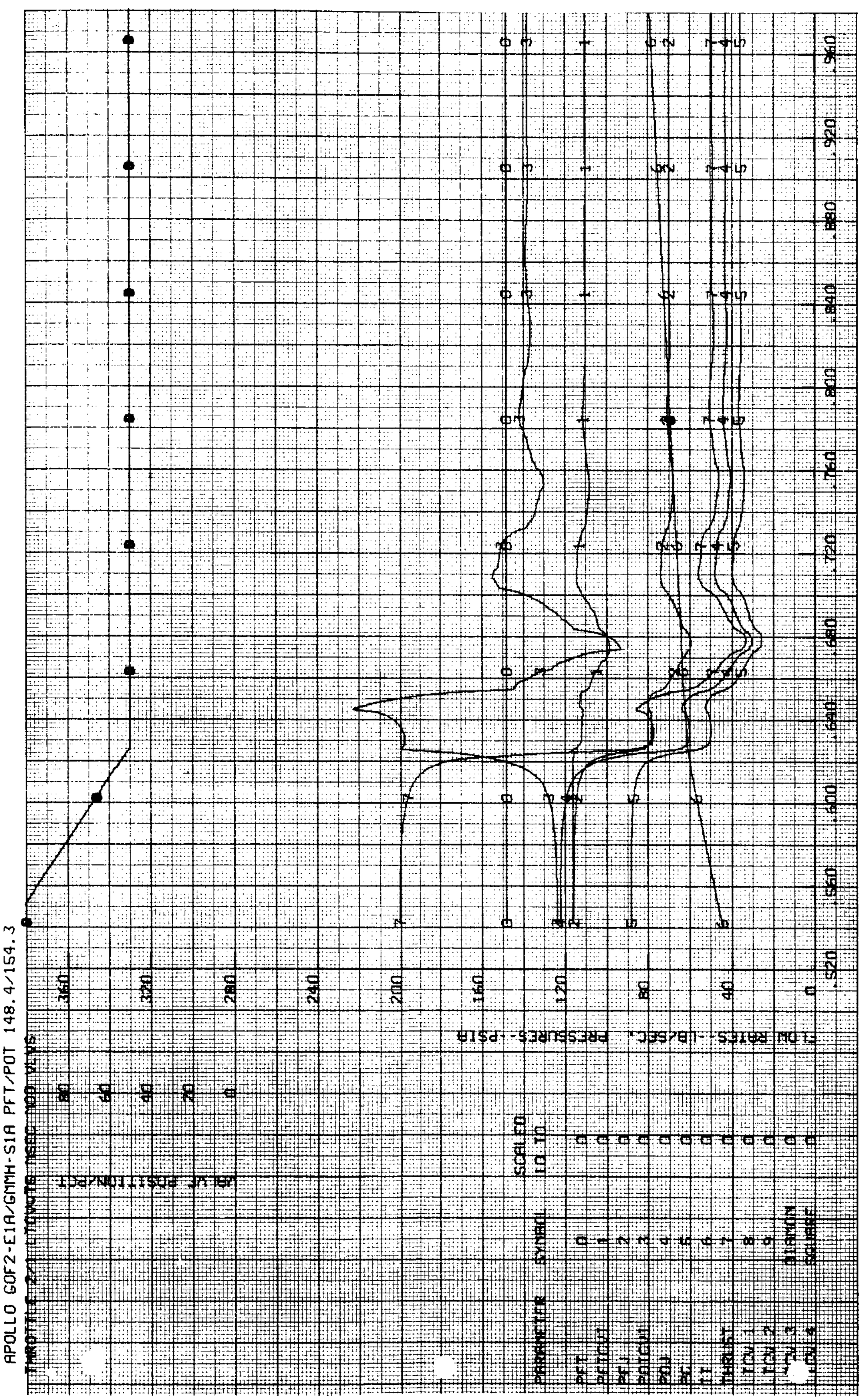
Apollo OF_2/MMH Throttling Transient, Part 1

Figure 31



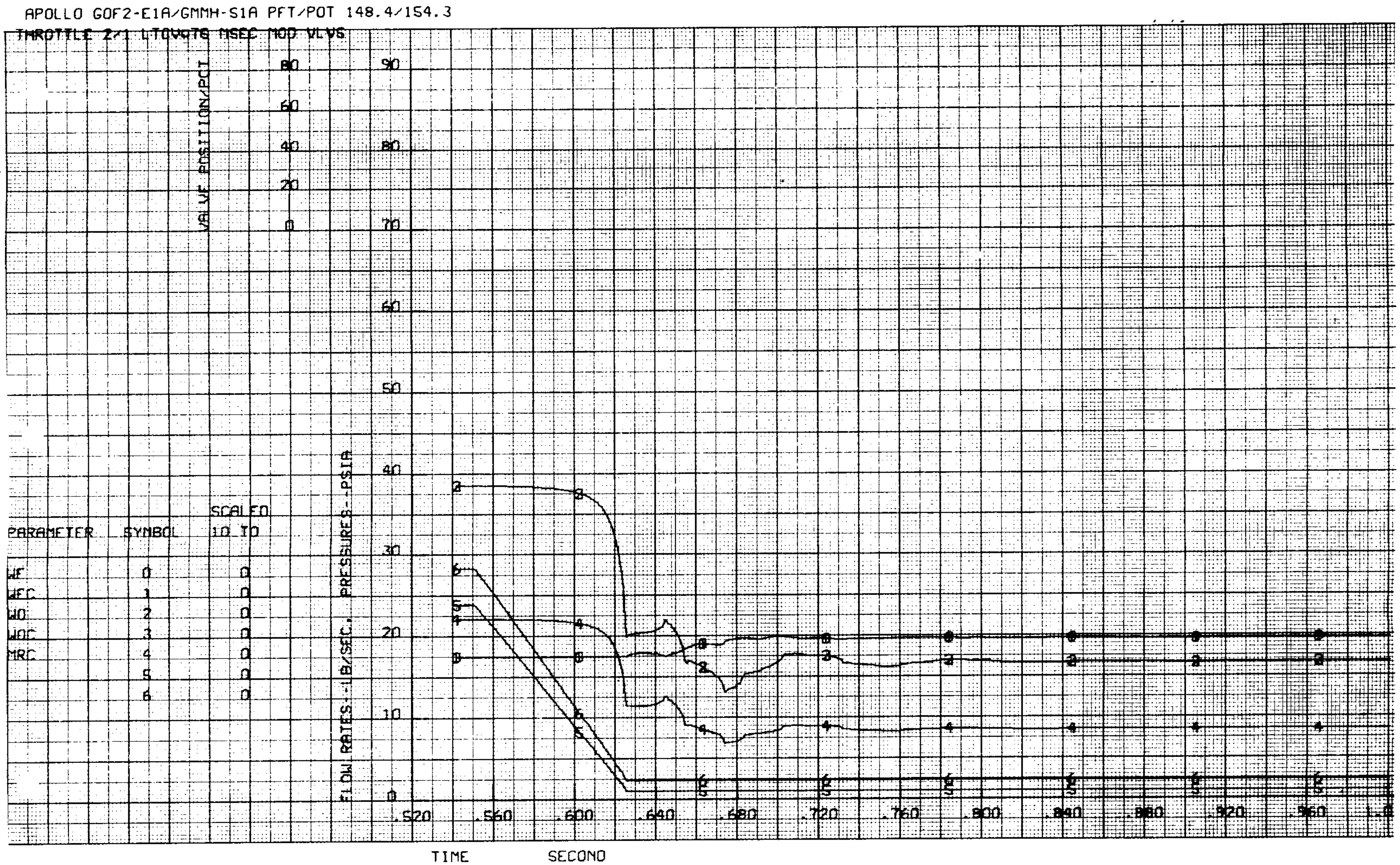
Apollo OF_2/MMH Throttling Transient, Part 2

Figure 32



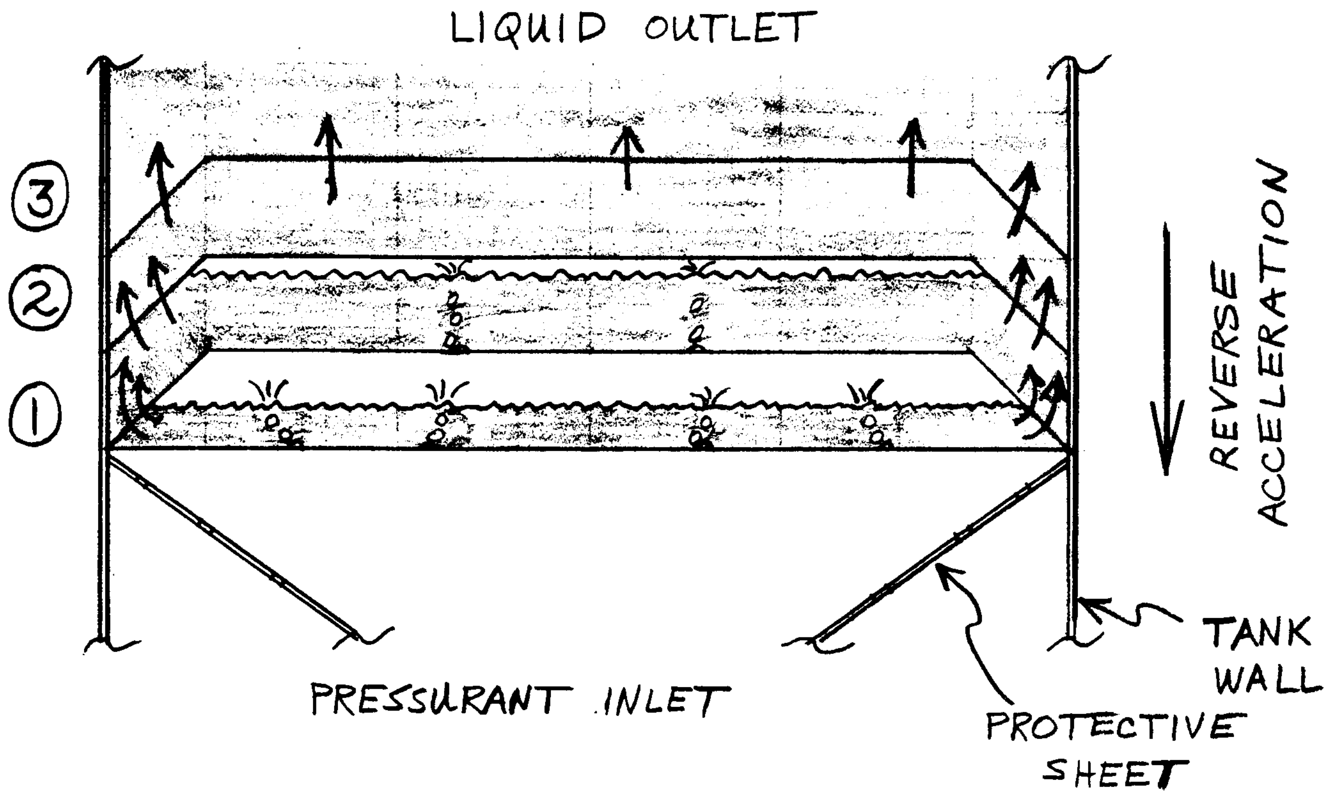
Apollo GOF_2-E1/GMMH-S1 Throttling Transient, Part 1

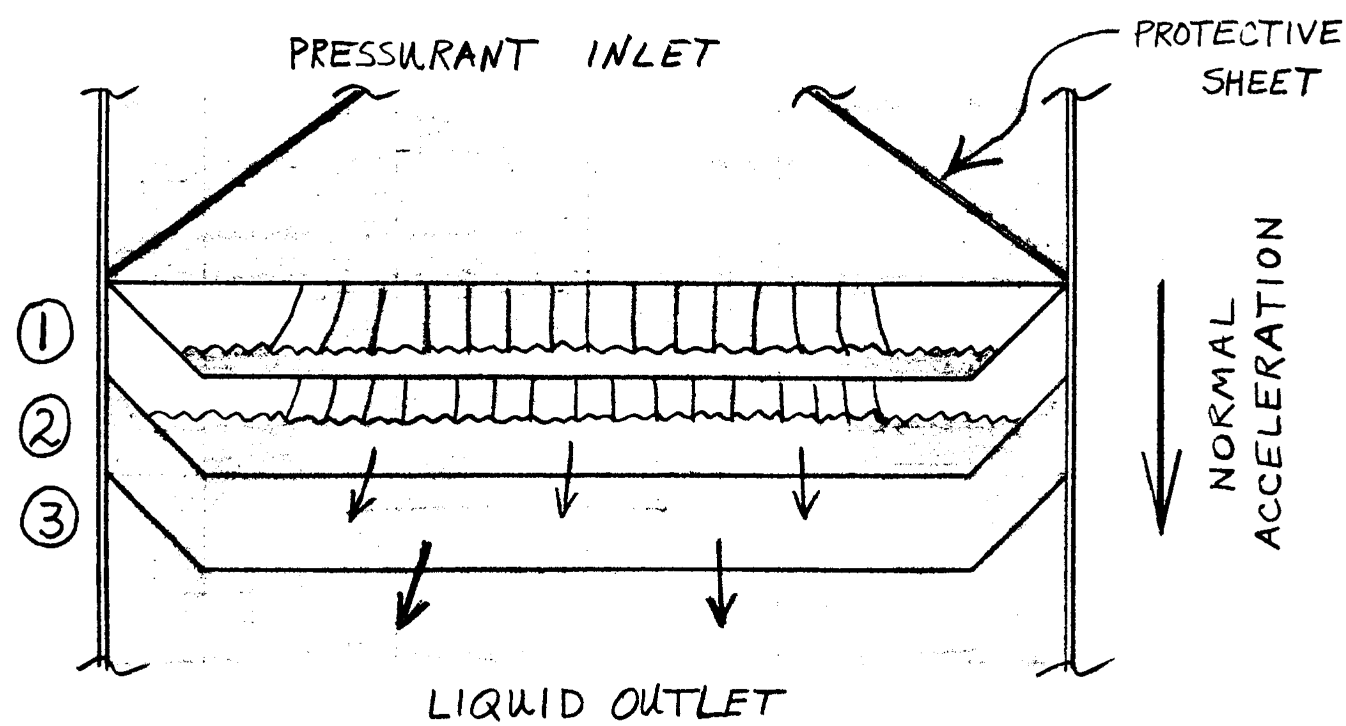
Figure 33



Apollo GOF_2-E1/GMMH-S1 Throttling Transient, Part 2

Figure 34

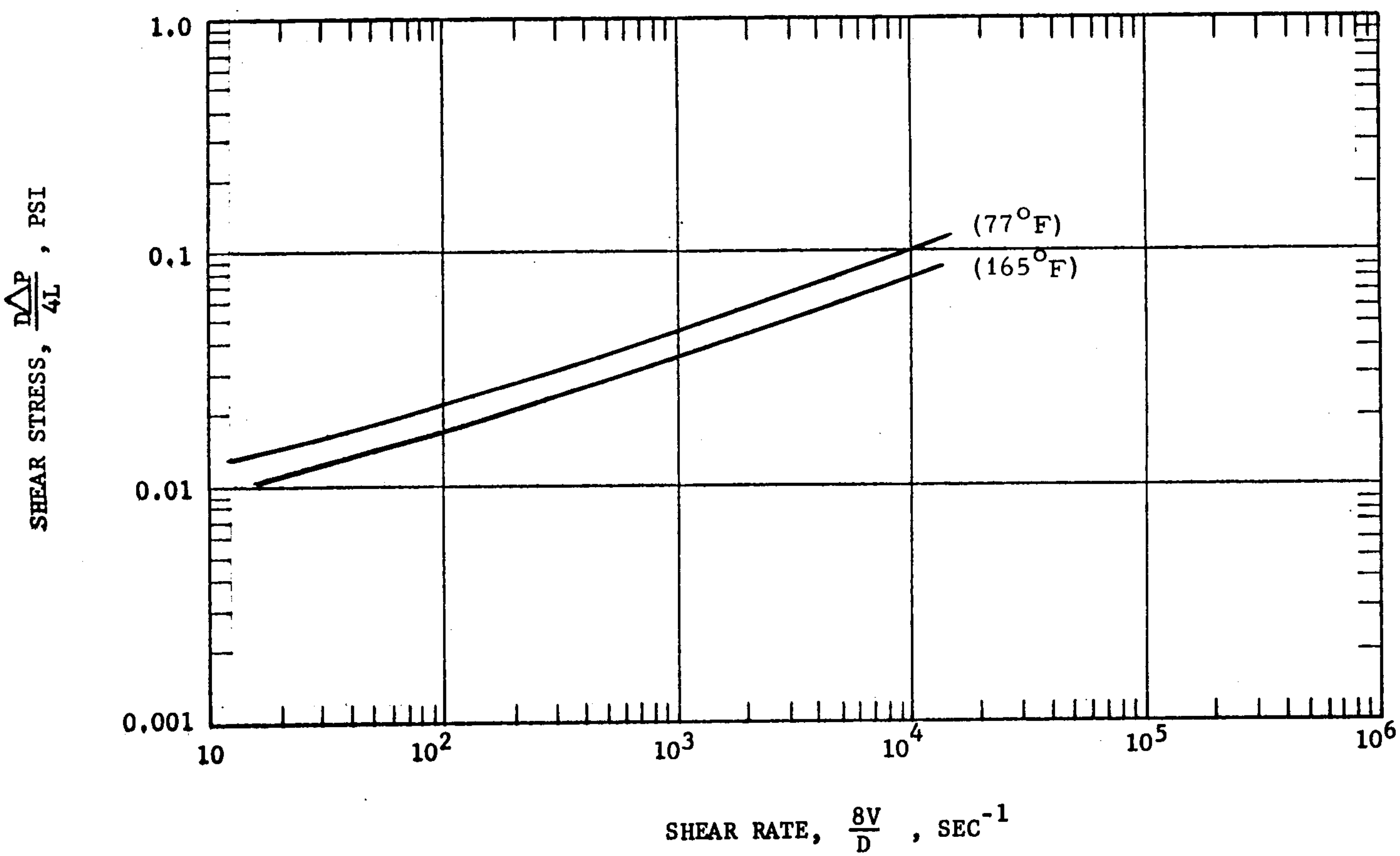




Operation of Propellant Containment Screens

Figure 35

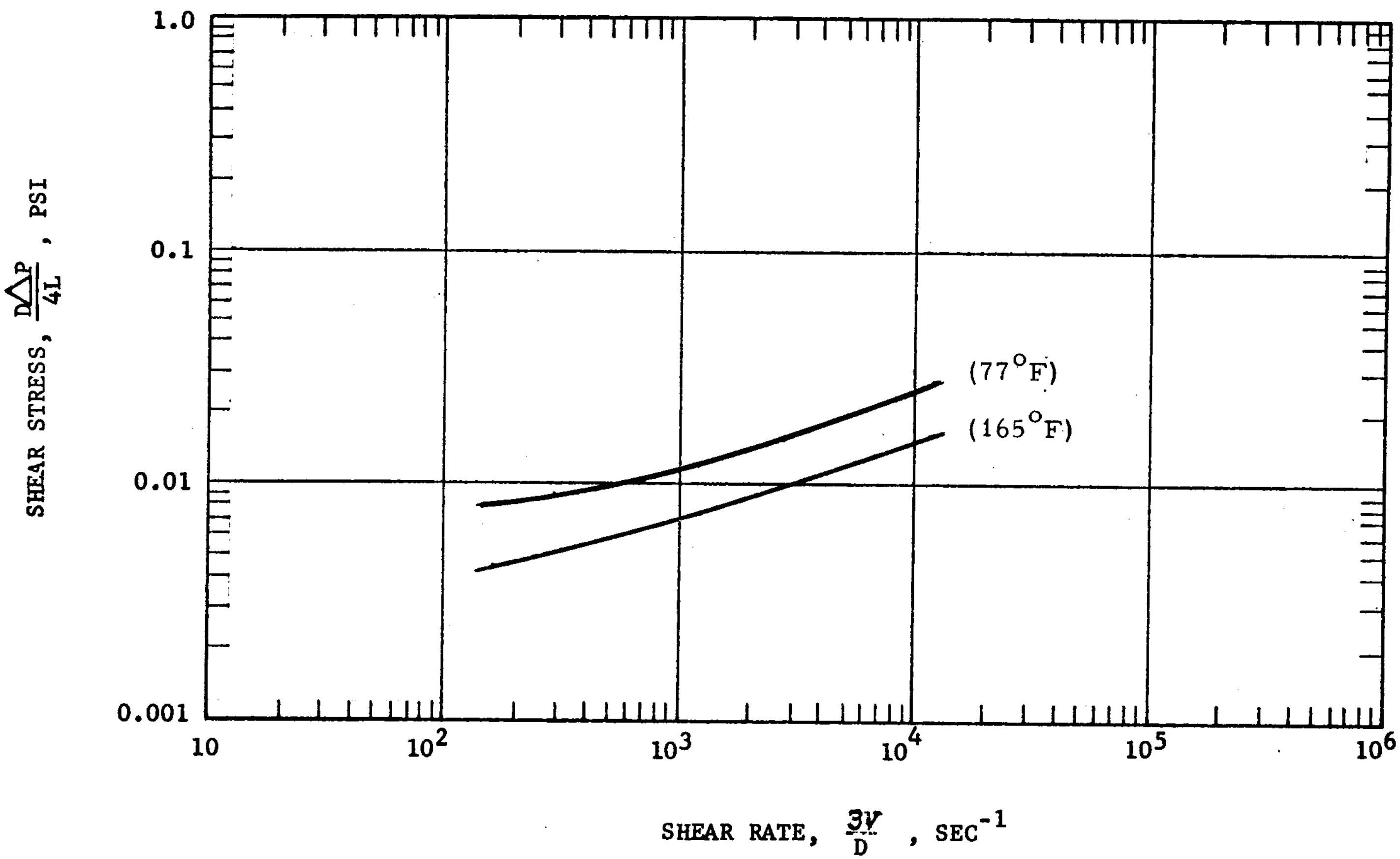
MEASUREMENT MADE WITH ASTM D-1092 CAPILLARY VISCOMETER, 77°F



Characteristic Flow Curve of Water Gelled with 0.27% Carbopol 940

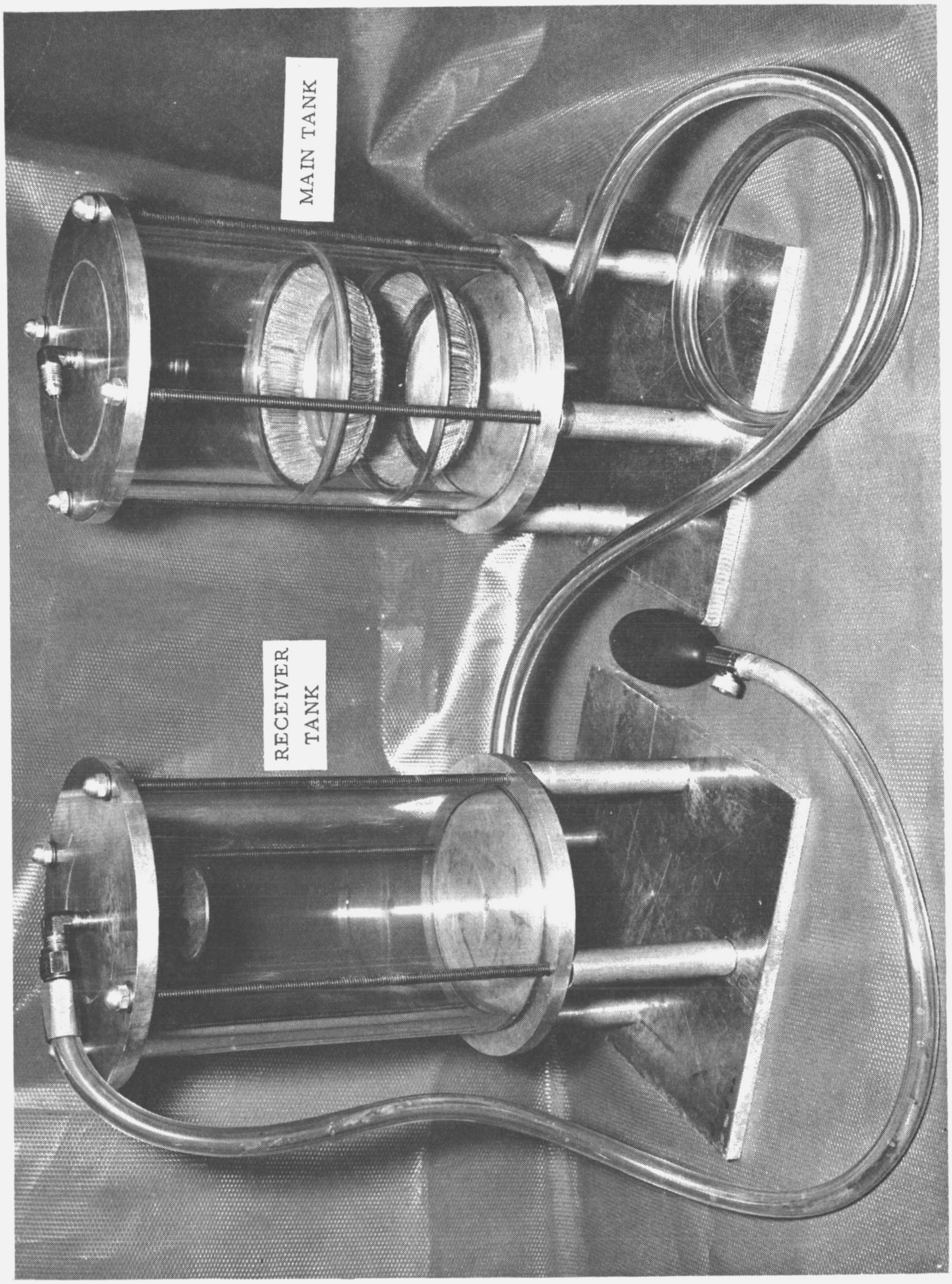
Figure 36

MEASUREMENT MADE WITH ASTM D-1092 CAPILLARY VISCOMETER, 77°F



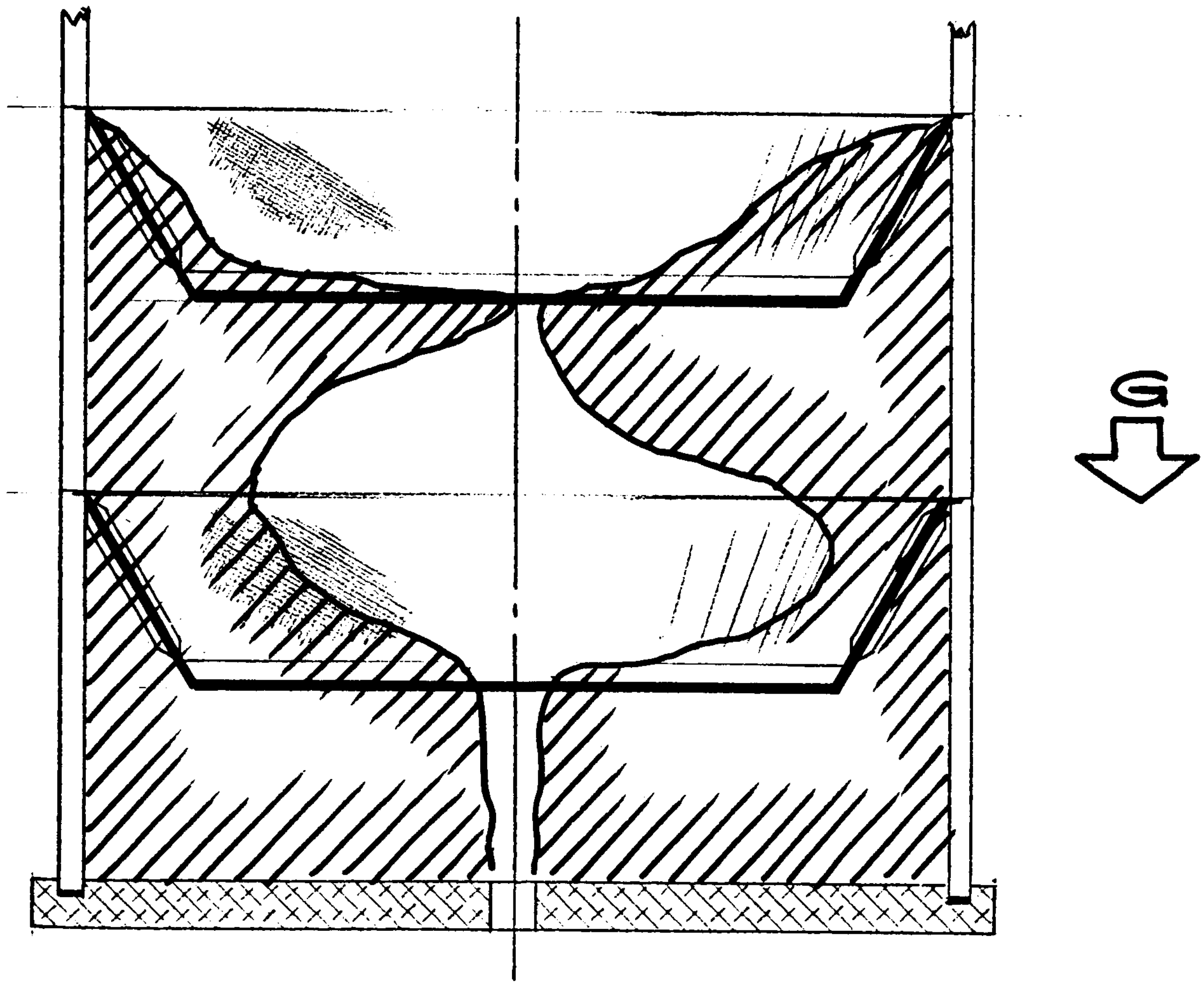
Characteristic Flow Curve of Water Gelled with 5.2% Santocel Z

Figure 37



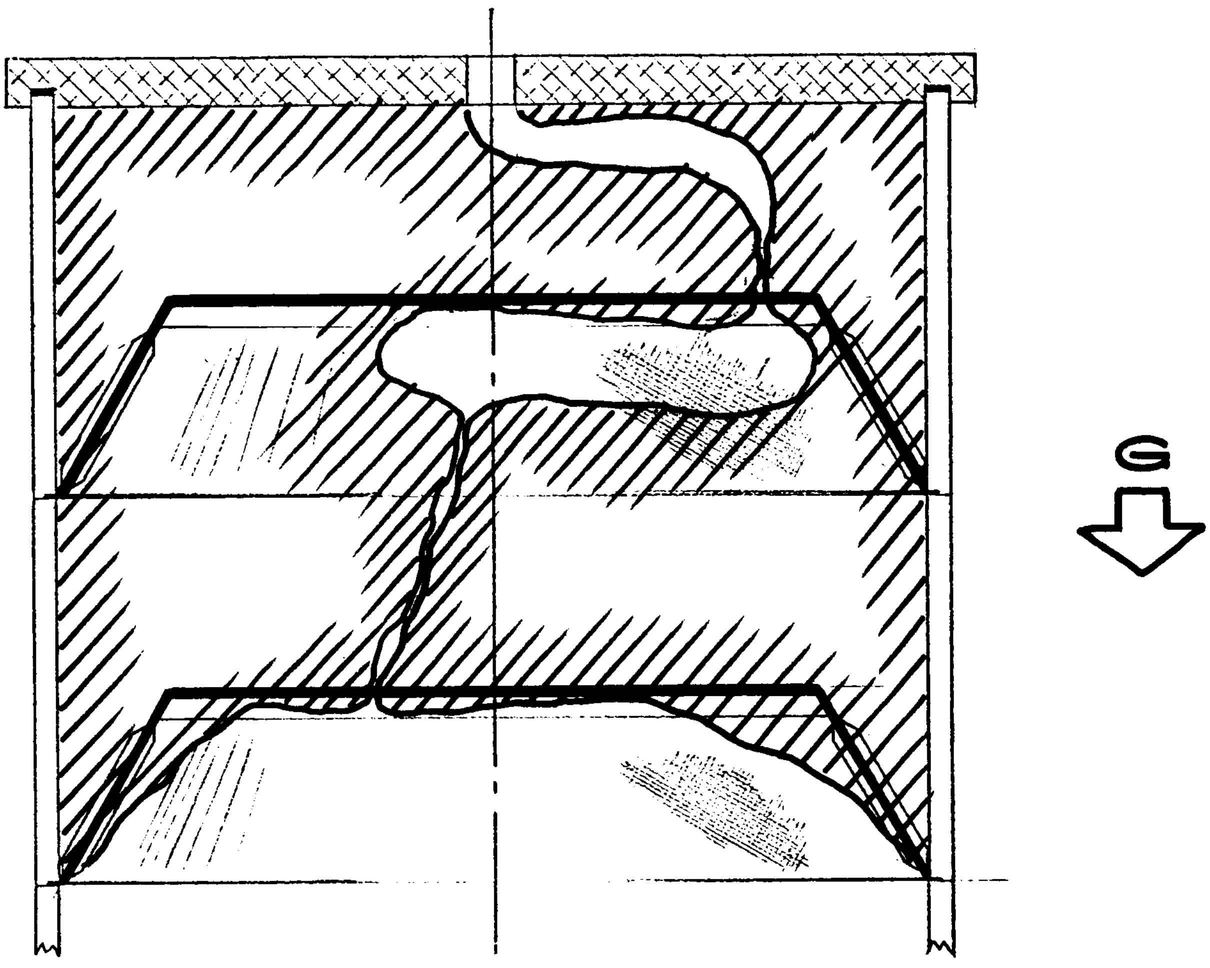
Expulsion System, Cylindrical Acrylic Tank

Figure 38



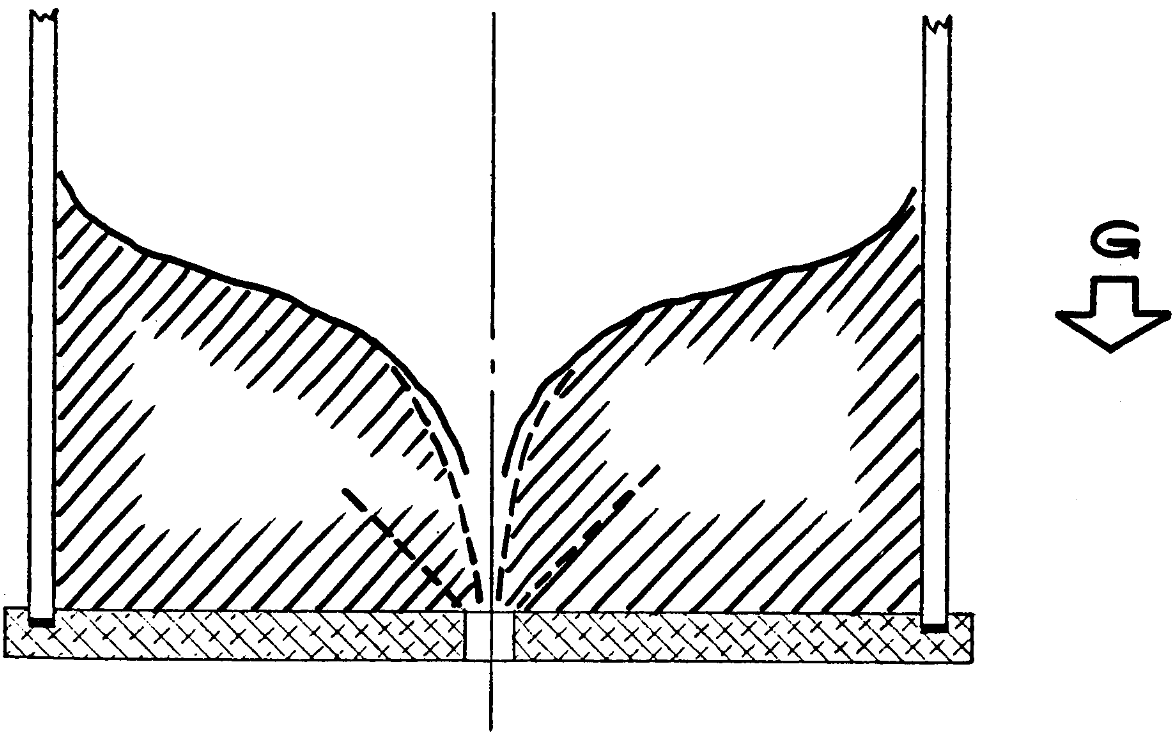
Organic Gel, Two Pie-Pans, Normal Expulsion

Figure 39



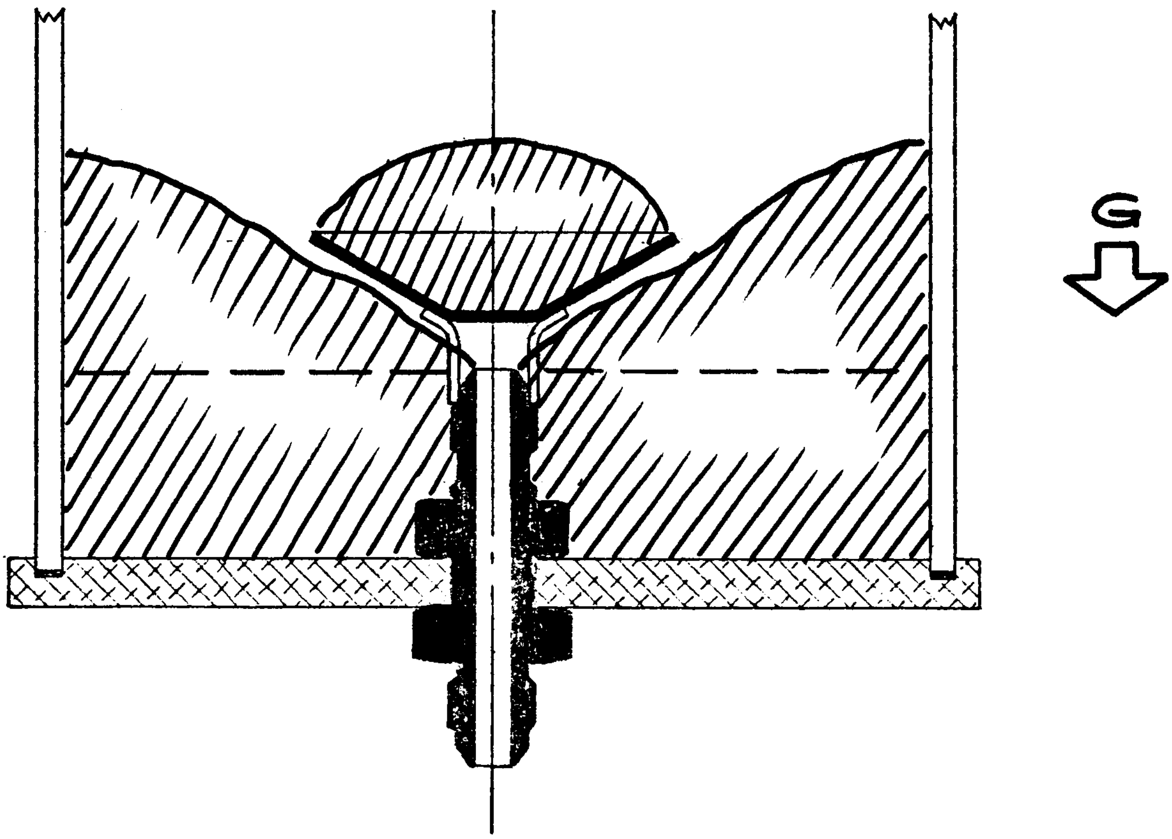
Organic Gel, Two Pie-Pans, Reverse Expulsion

Figure 40



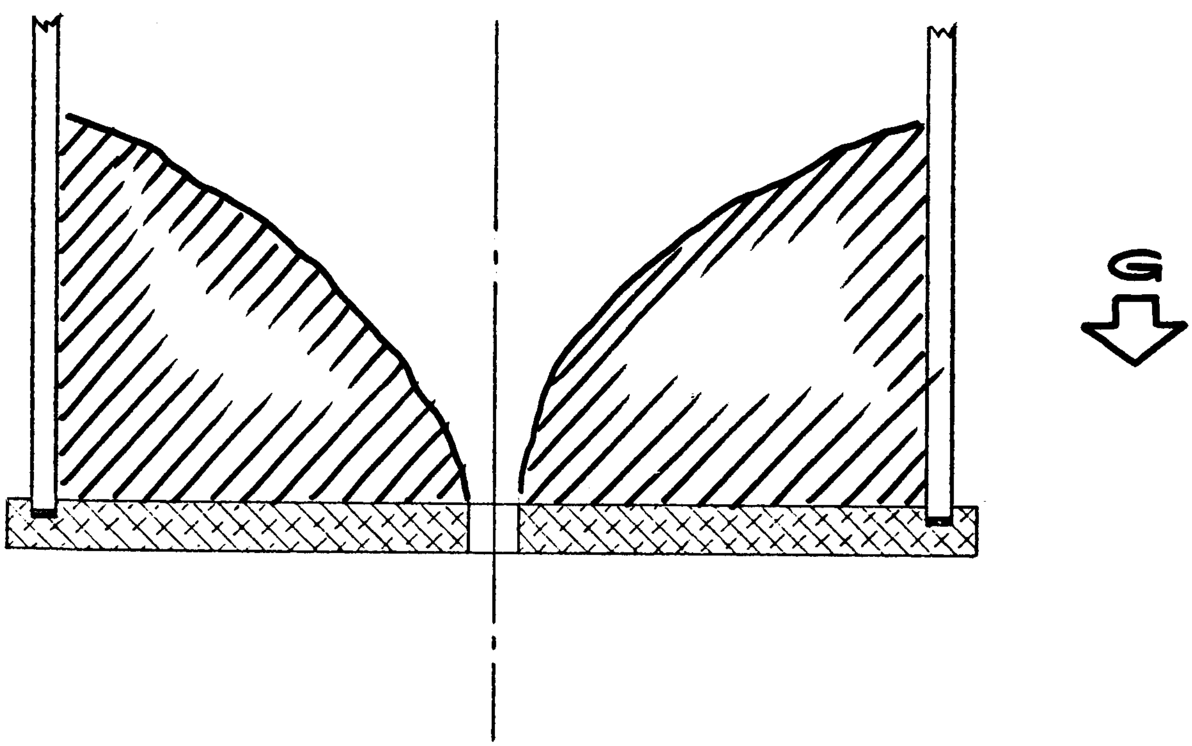
Organic Gel, Umbaffled Expulsion

Figure 41



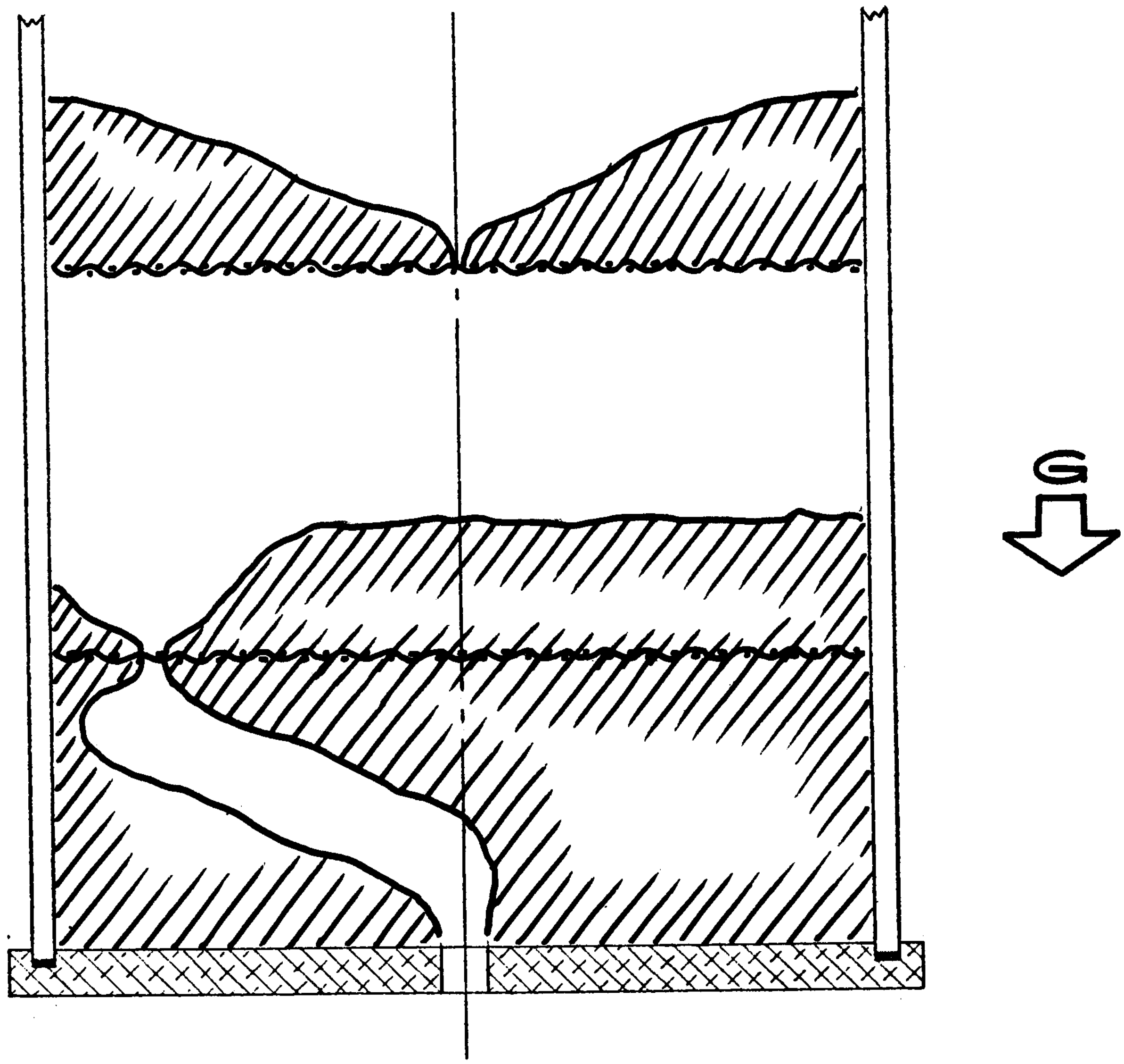
Organic Gel, Baffled Expulsion

Figure 42



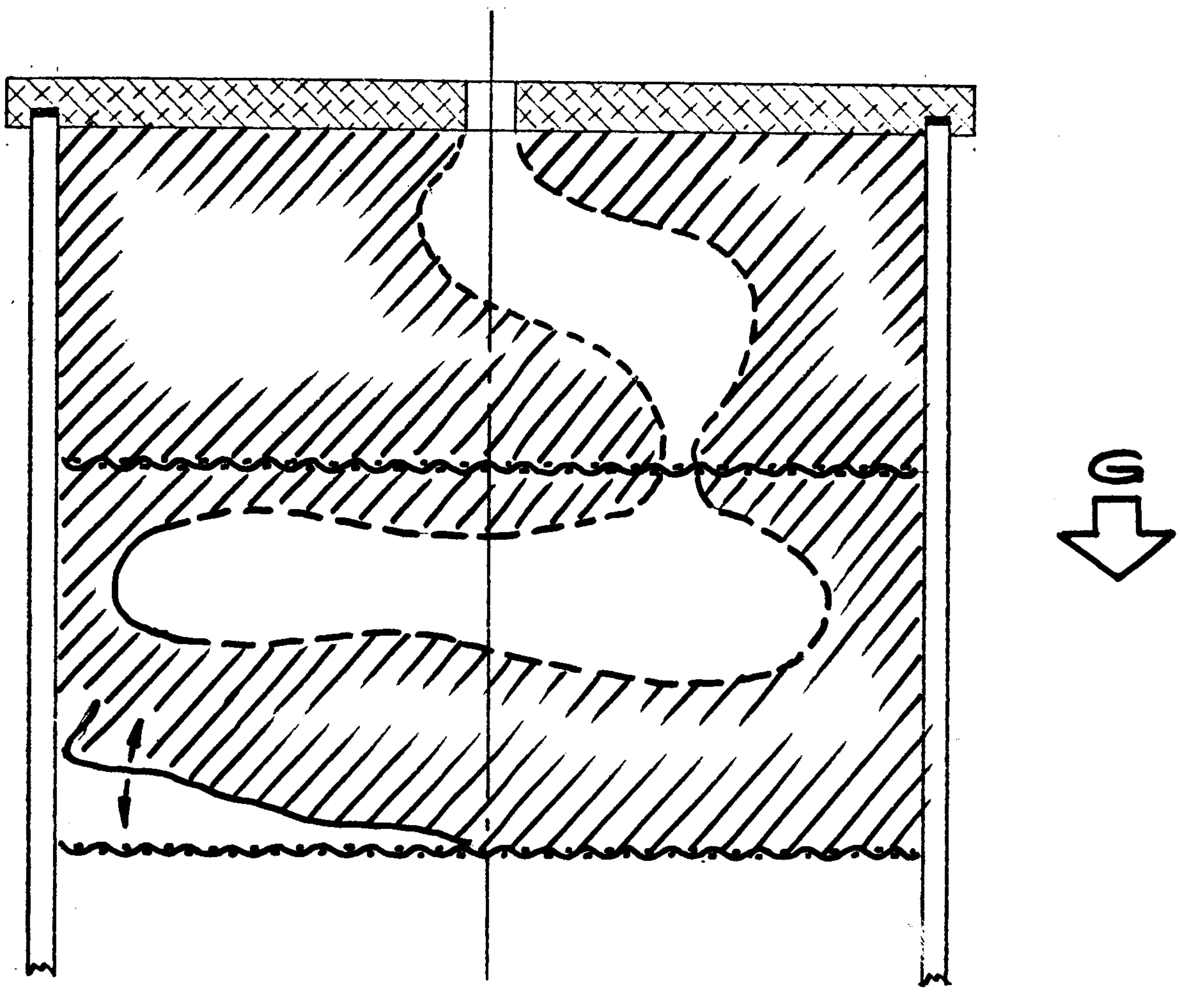
Particulate Gel, Unbaffled Expulsion

Figure 43



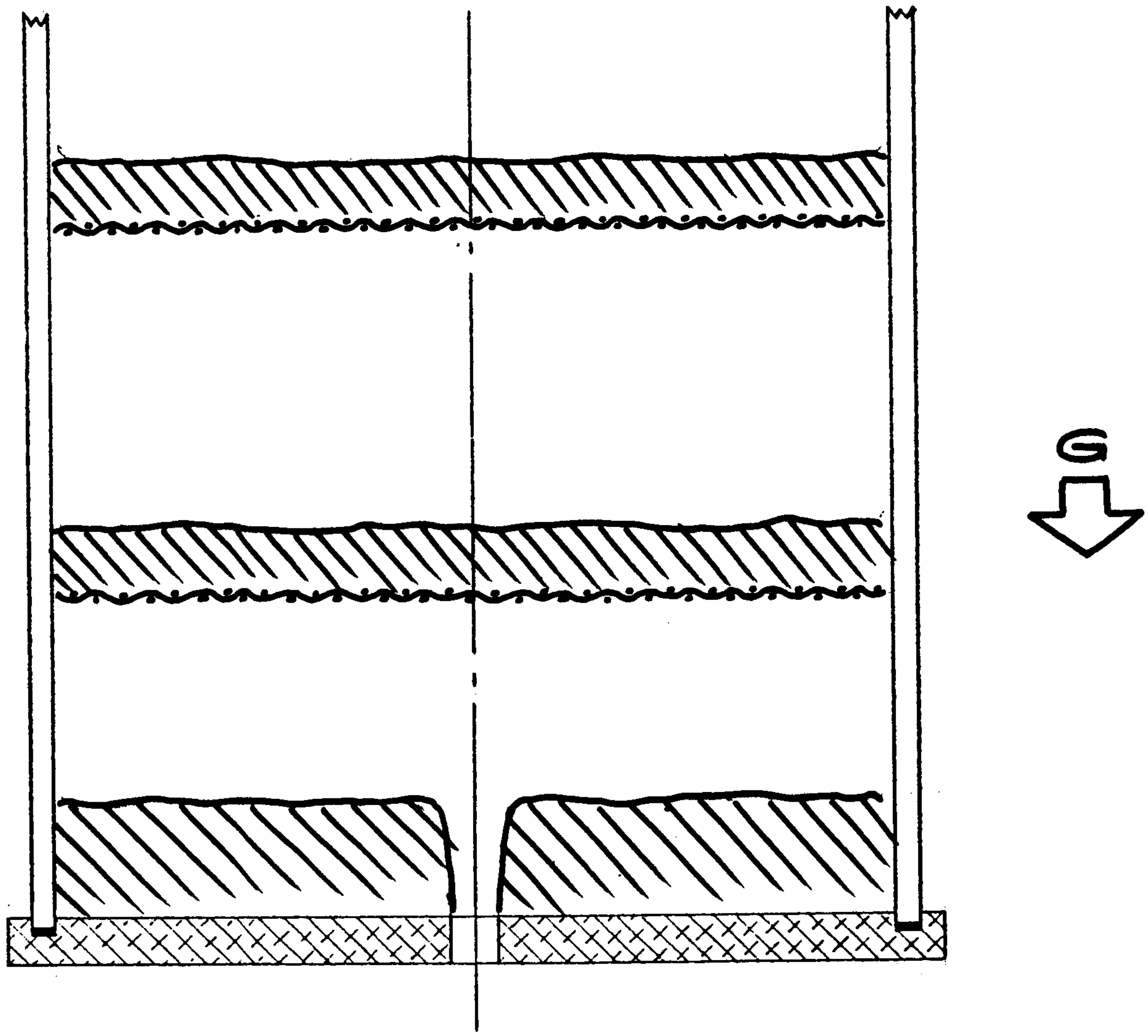
Particulate Gel, Flat Screens, Normal Expulsion

Figure 44



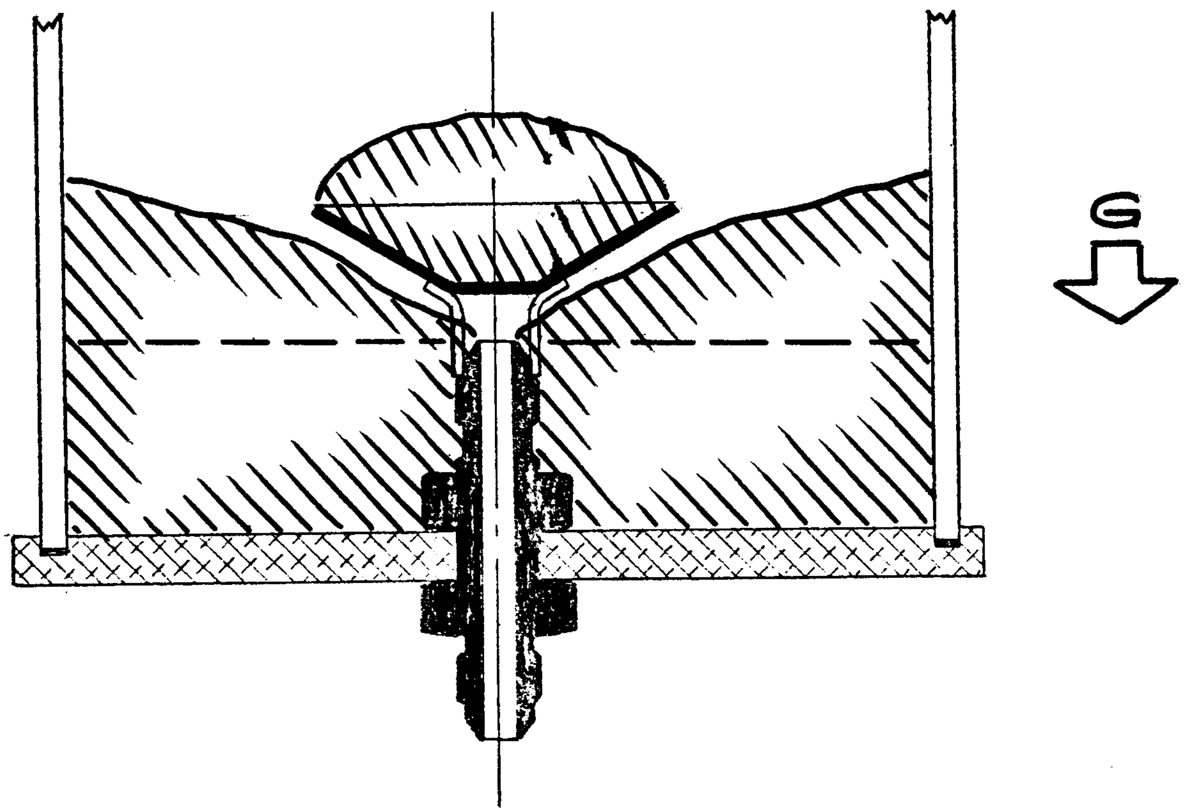
Particulate Gel, Flat Screens, Reverse Expulsion

Figure 45



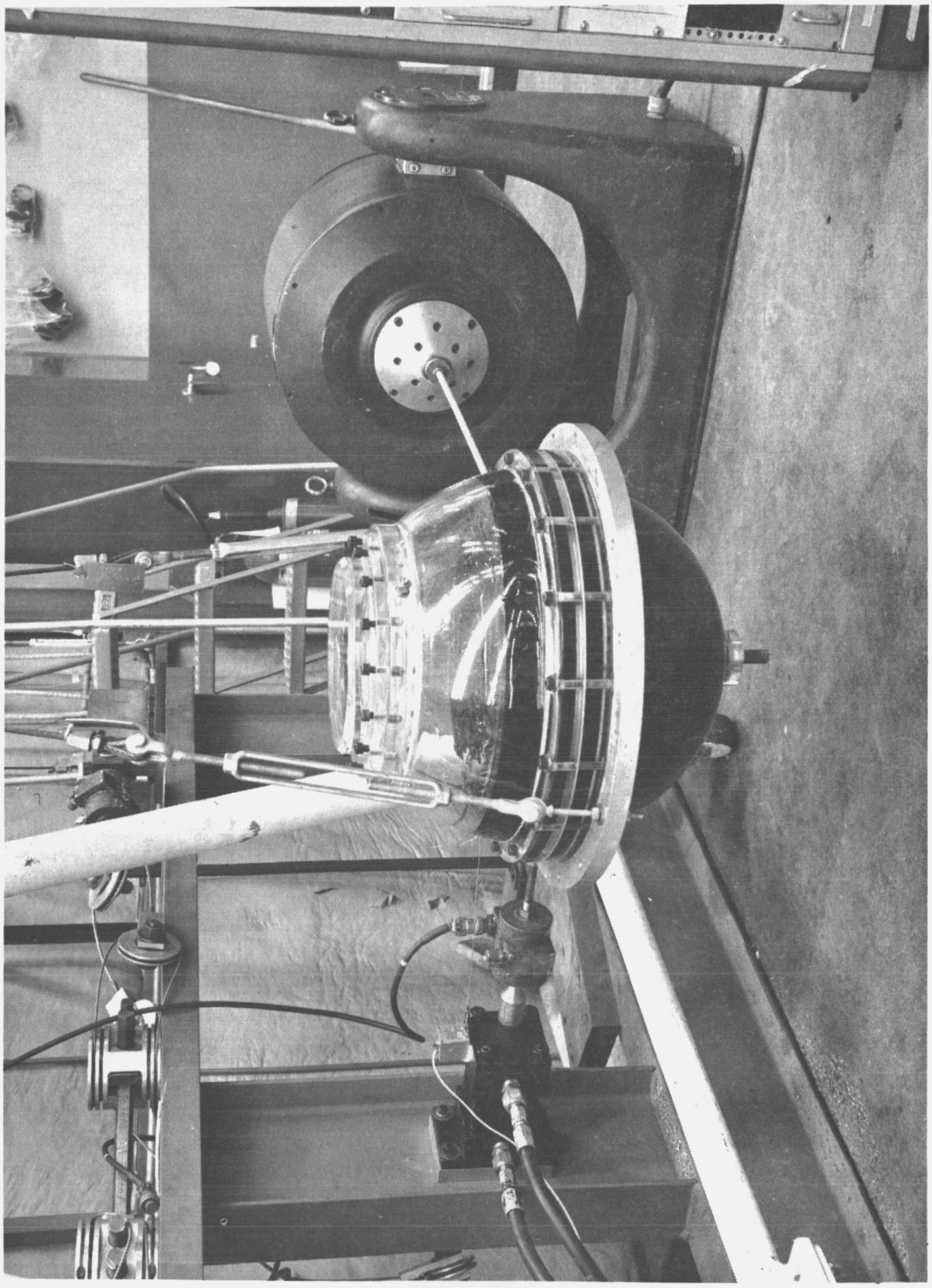
Particulate Gel, Flat Screens, Normal Expulsion with Sloshing

Figure 46



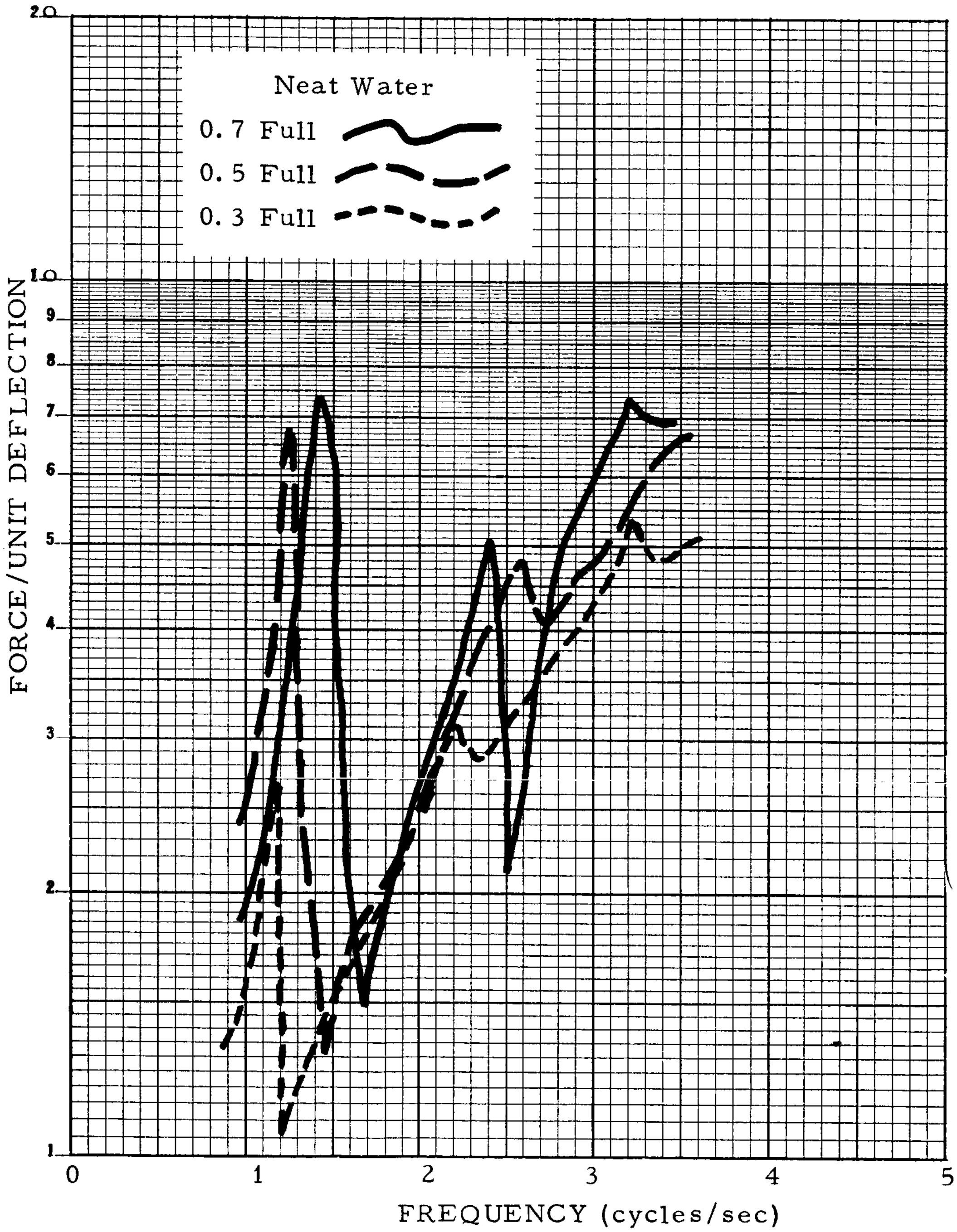
Particulate Gel, Baffled Expulsion

Figure 47



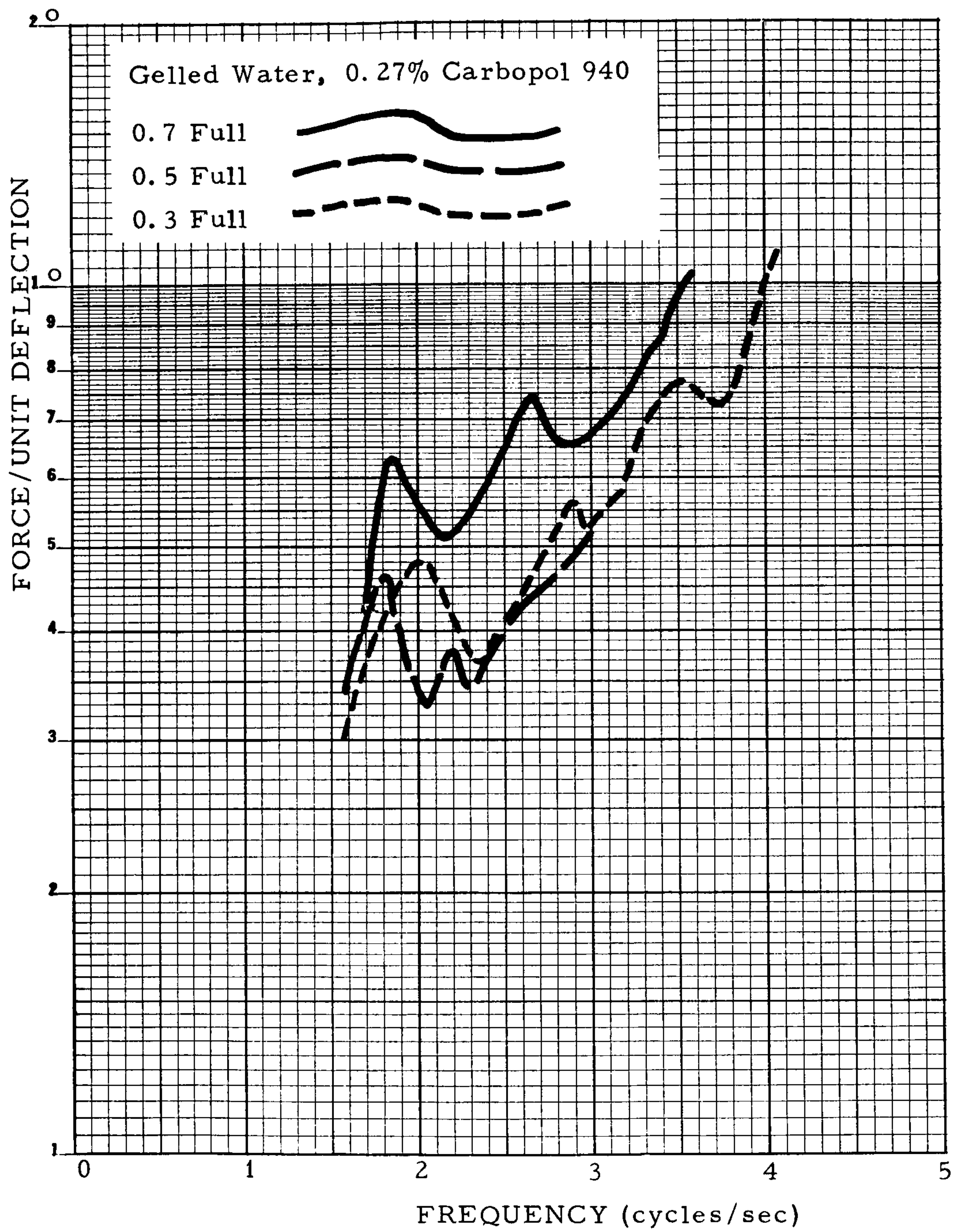
Slosh Test Setup

Figure 48



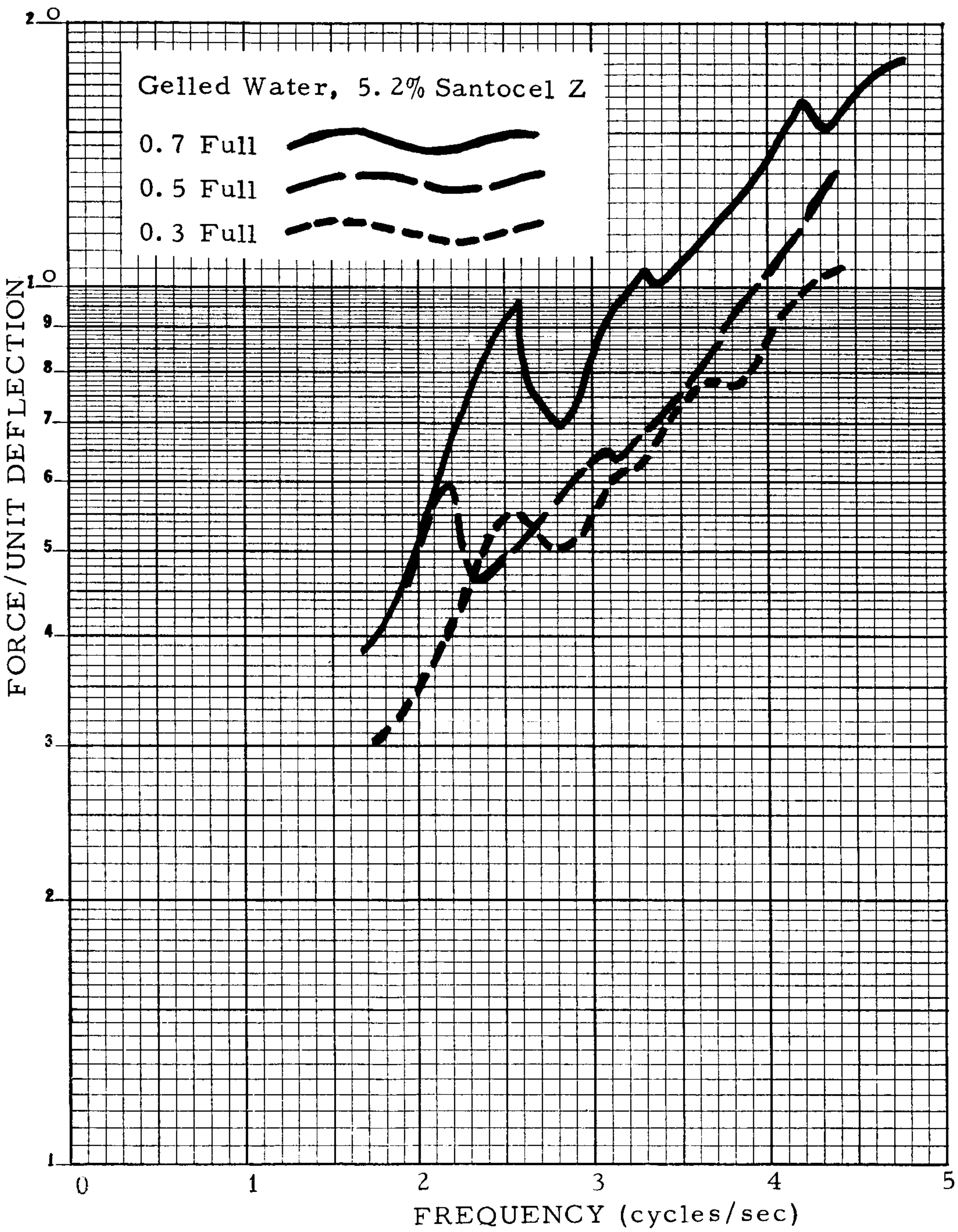
Slosh Response Curve, Neat Water

Figure 49



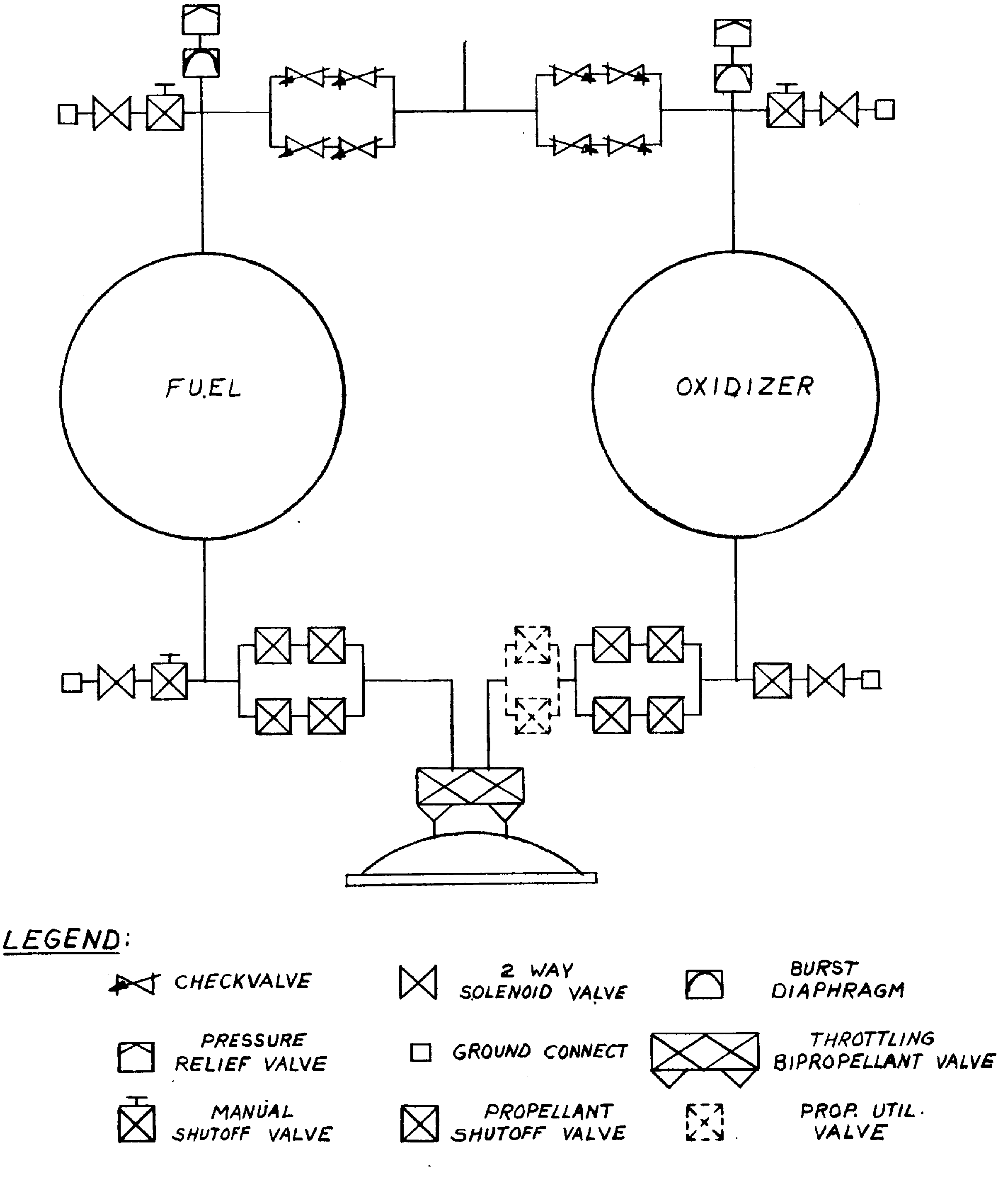
Slosh Response Curve, Water Gelled with 0.27% Carbopol

Figure 50



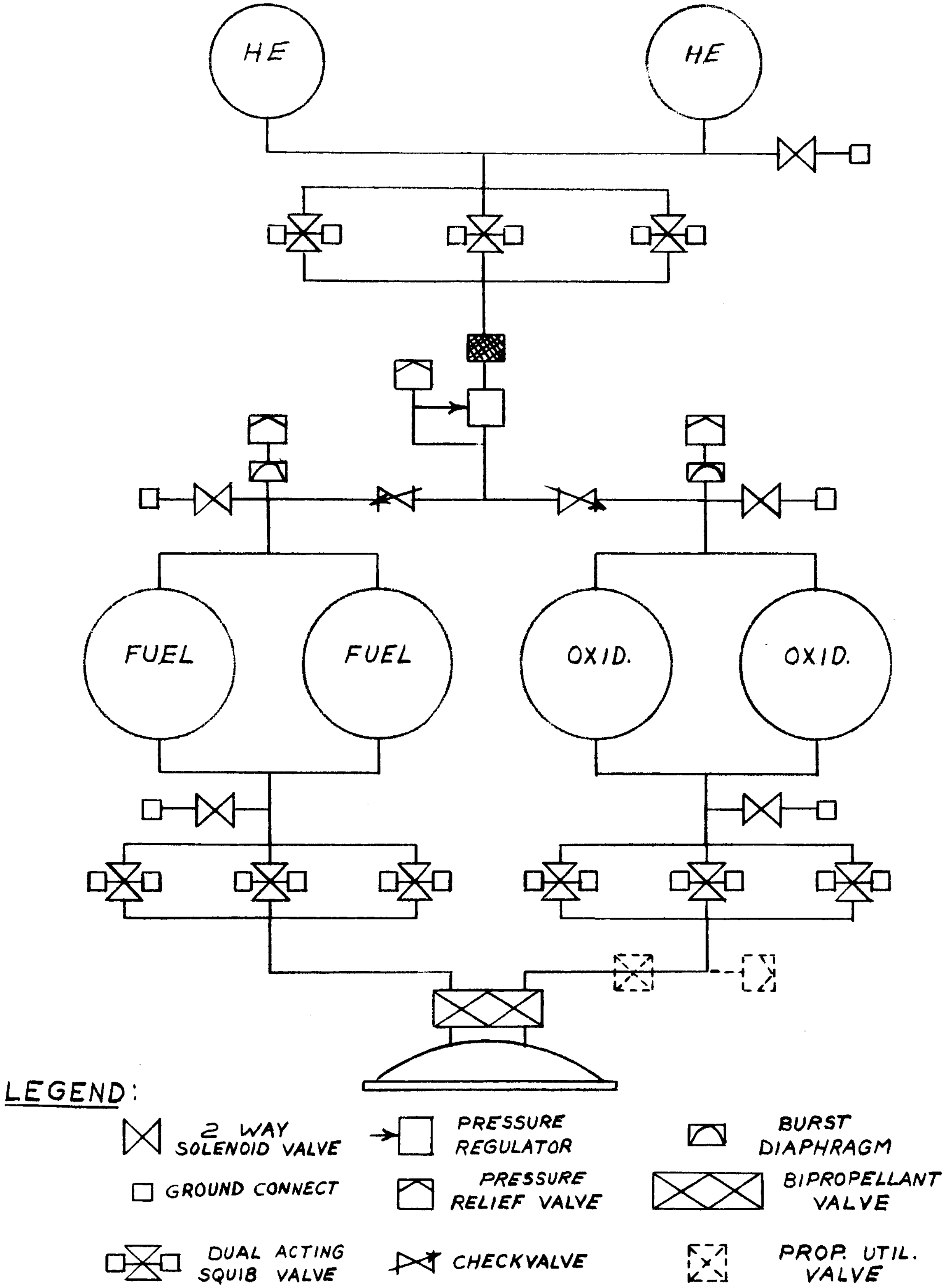
Slosh Response Curve, Water Gelled with 5.2% Santocel Z

Figure 51



Typical Engine Schematic for Lunar Descent and Ascent

Figure 52



Typical Engine Schematic for Space Probe

10-17-66

Figure 53

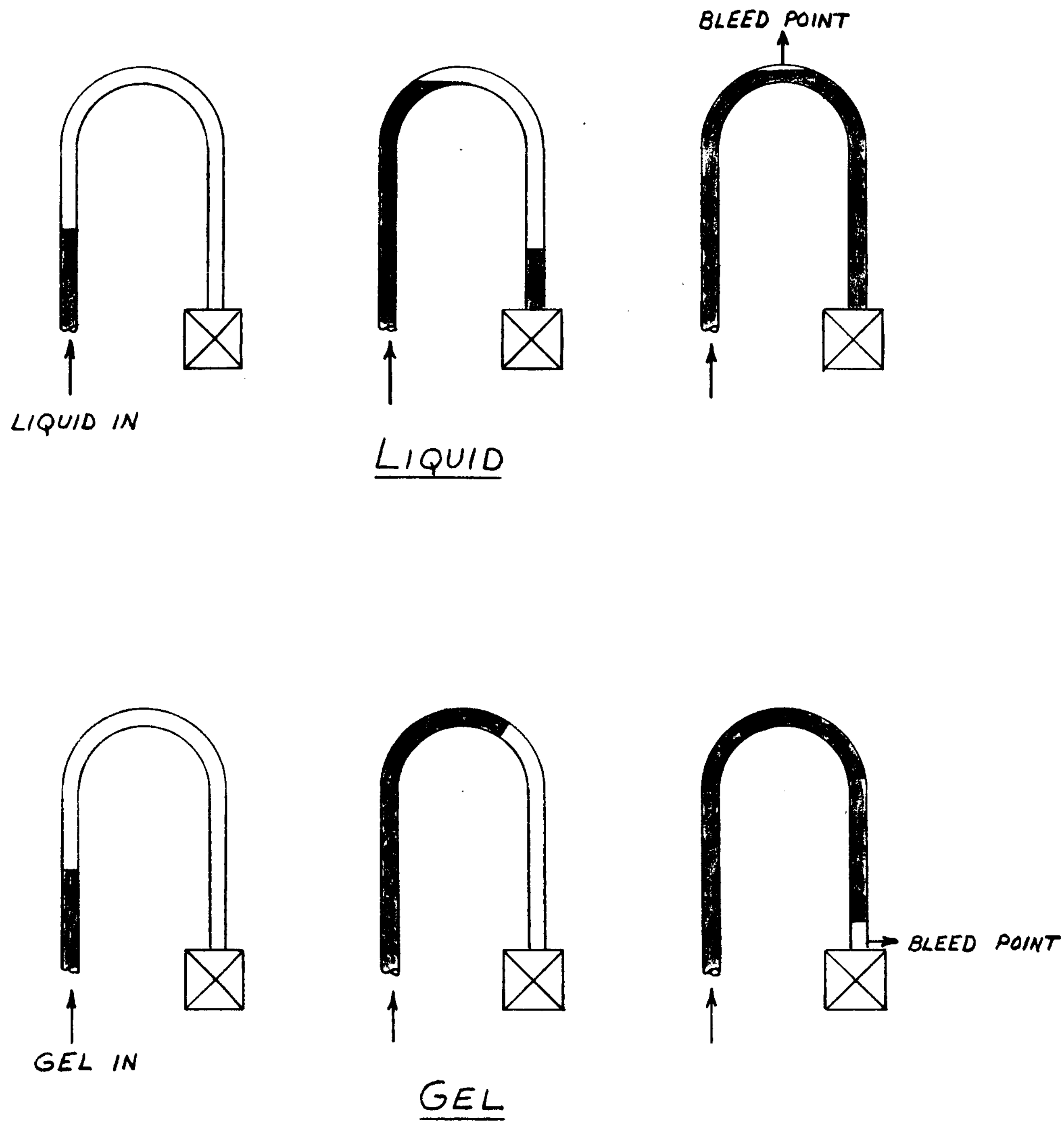
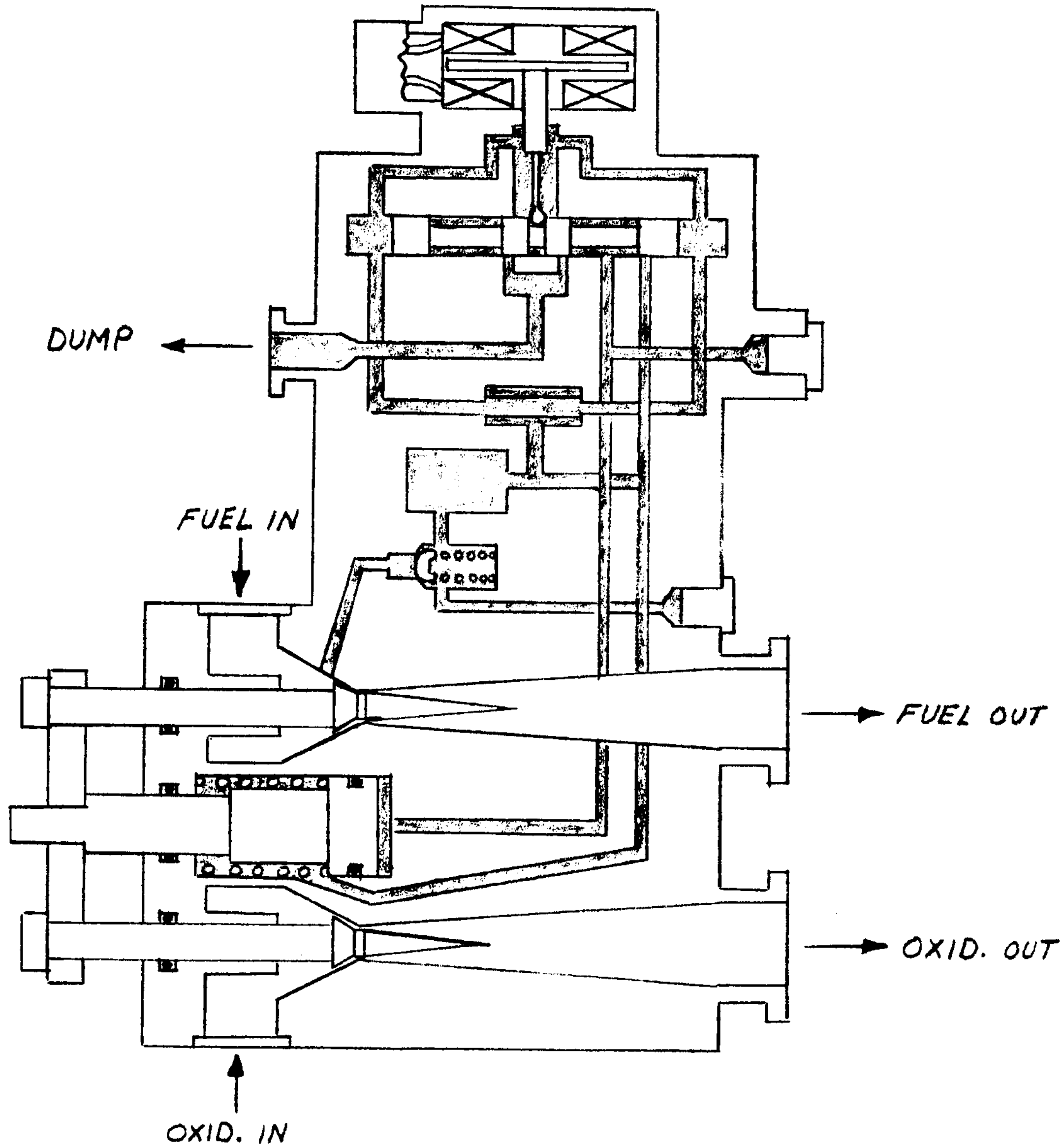


Illustration of Bleed-In

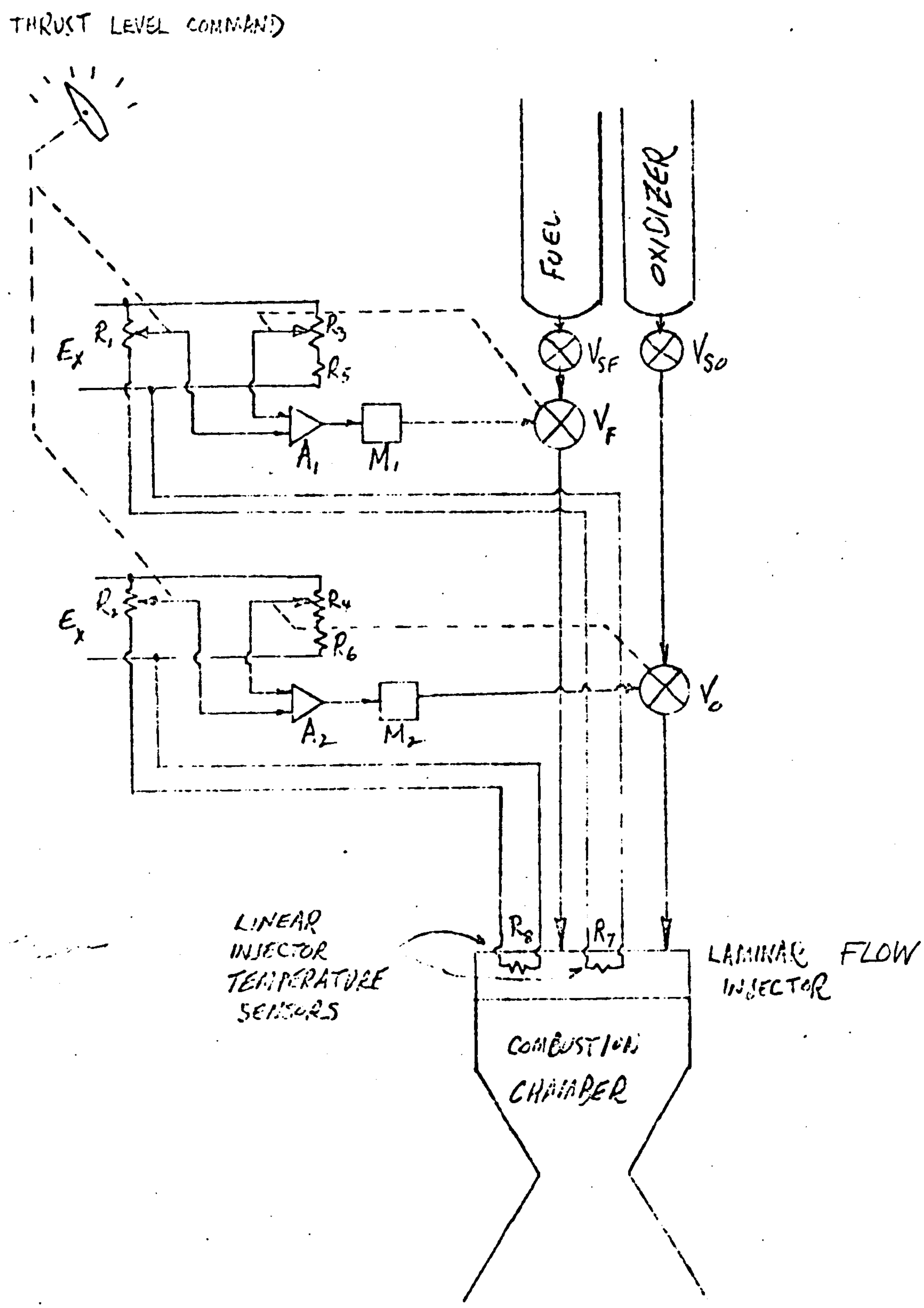
Figure 54



NOTE: SHADED AREAS SHOW FUEL PASSAGES

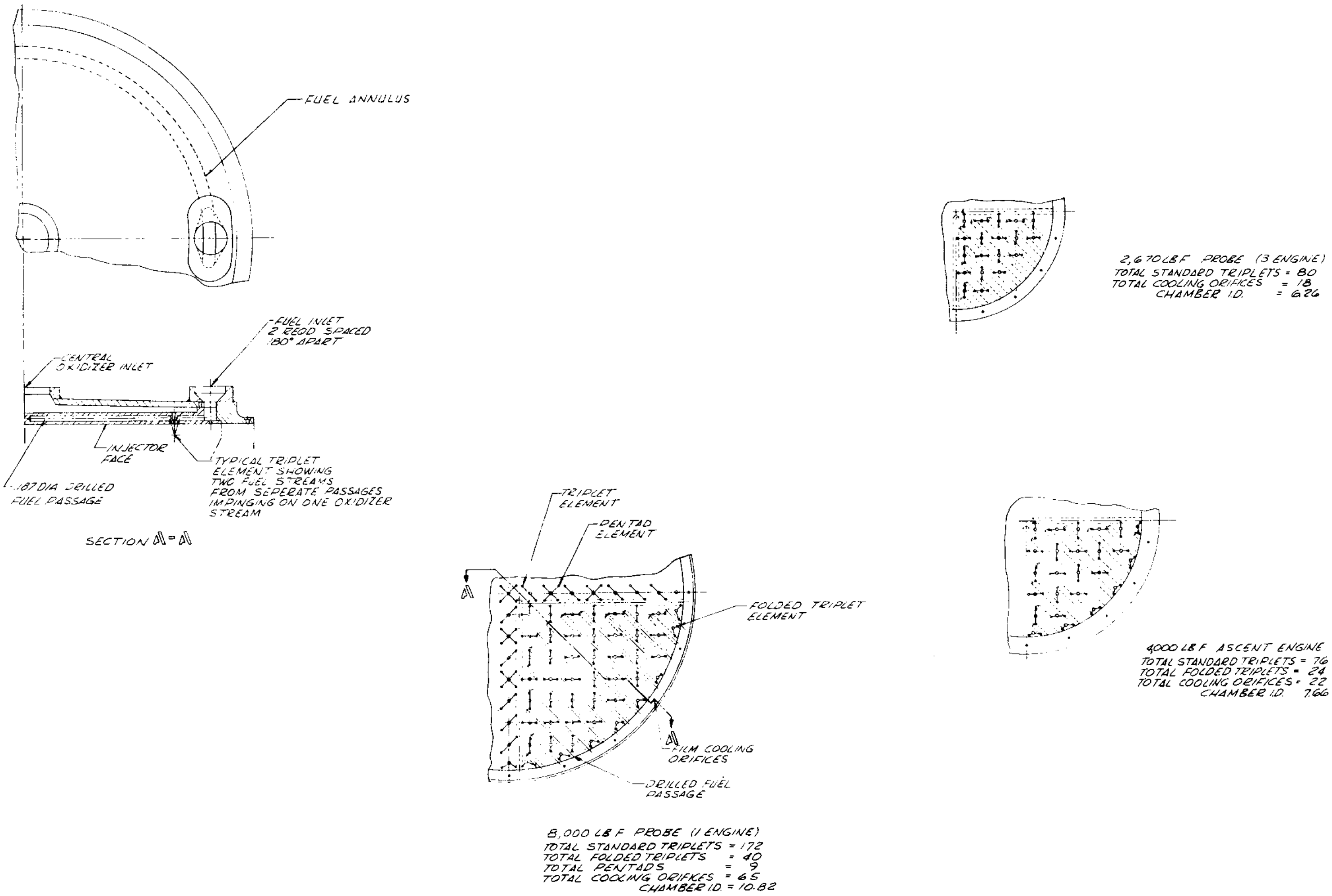
Typical Schematic Hydraulically Actuated Throttling Valve

Figure 55



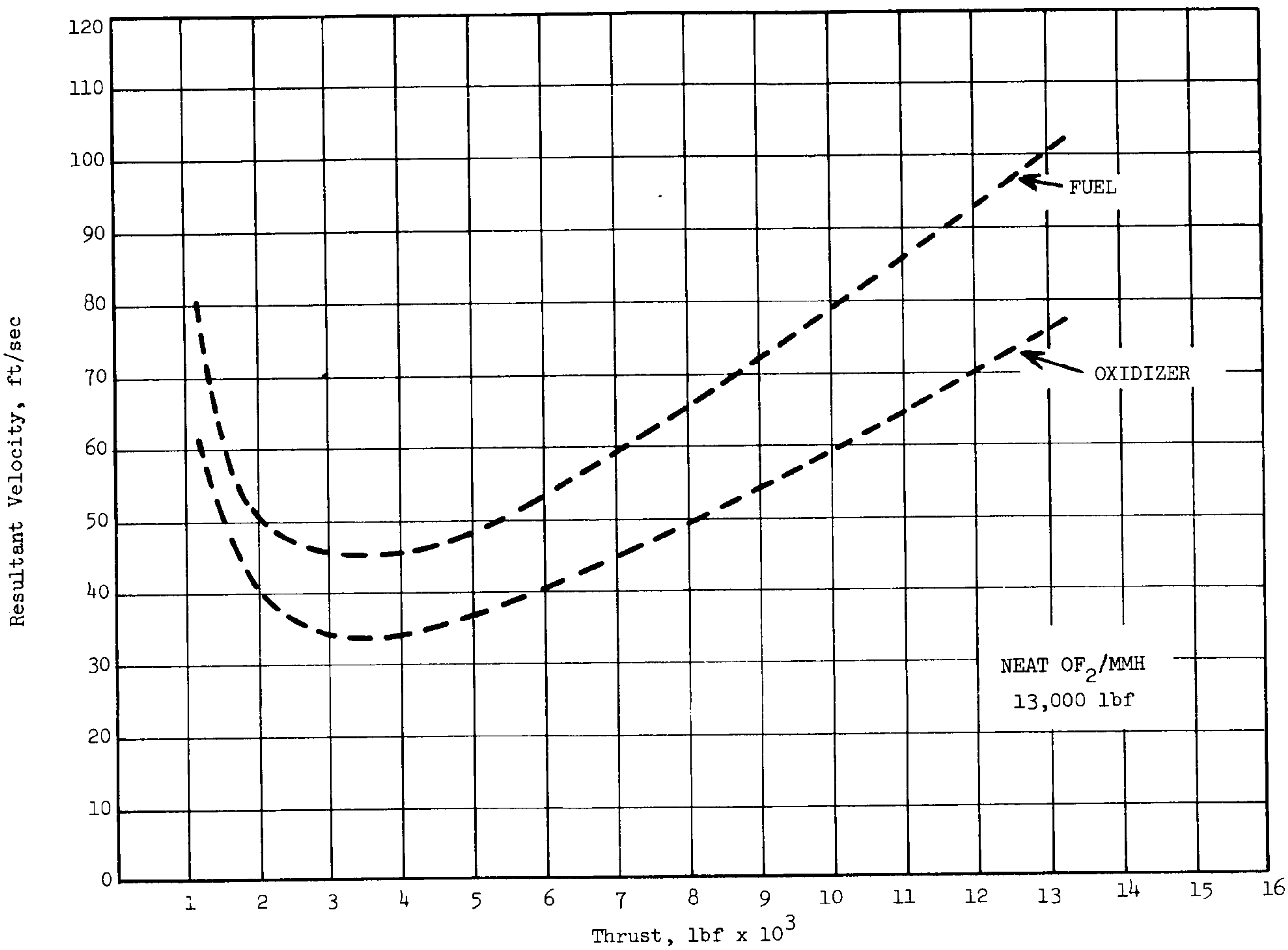
Gel Laminar Flow Control System

Figure 56



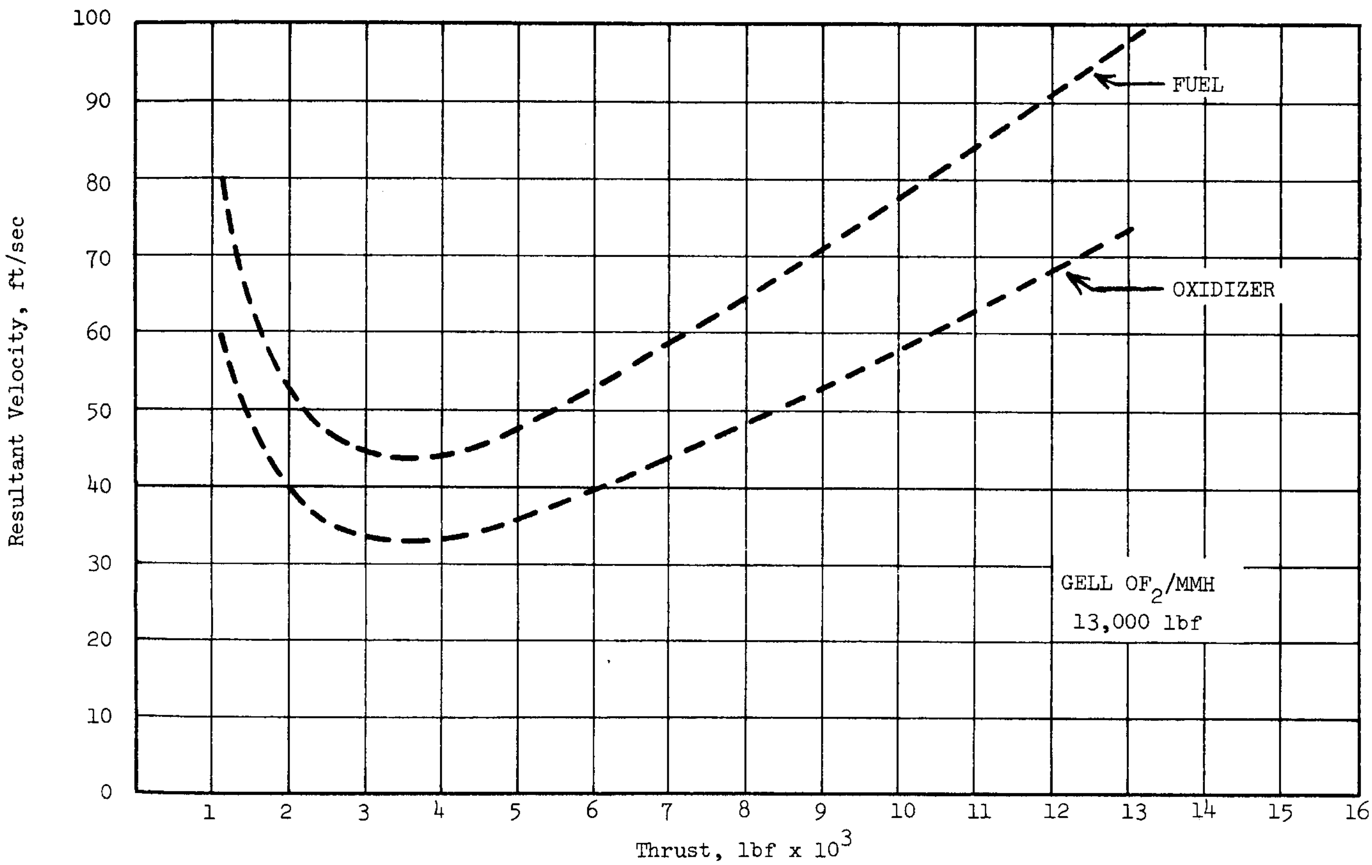
Conventional Triplet Element Injectors

Figure 57



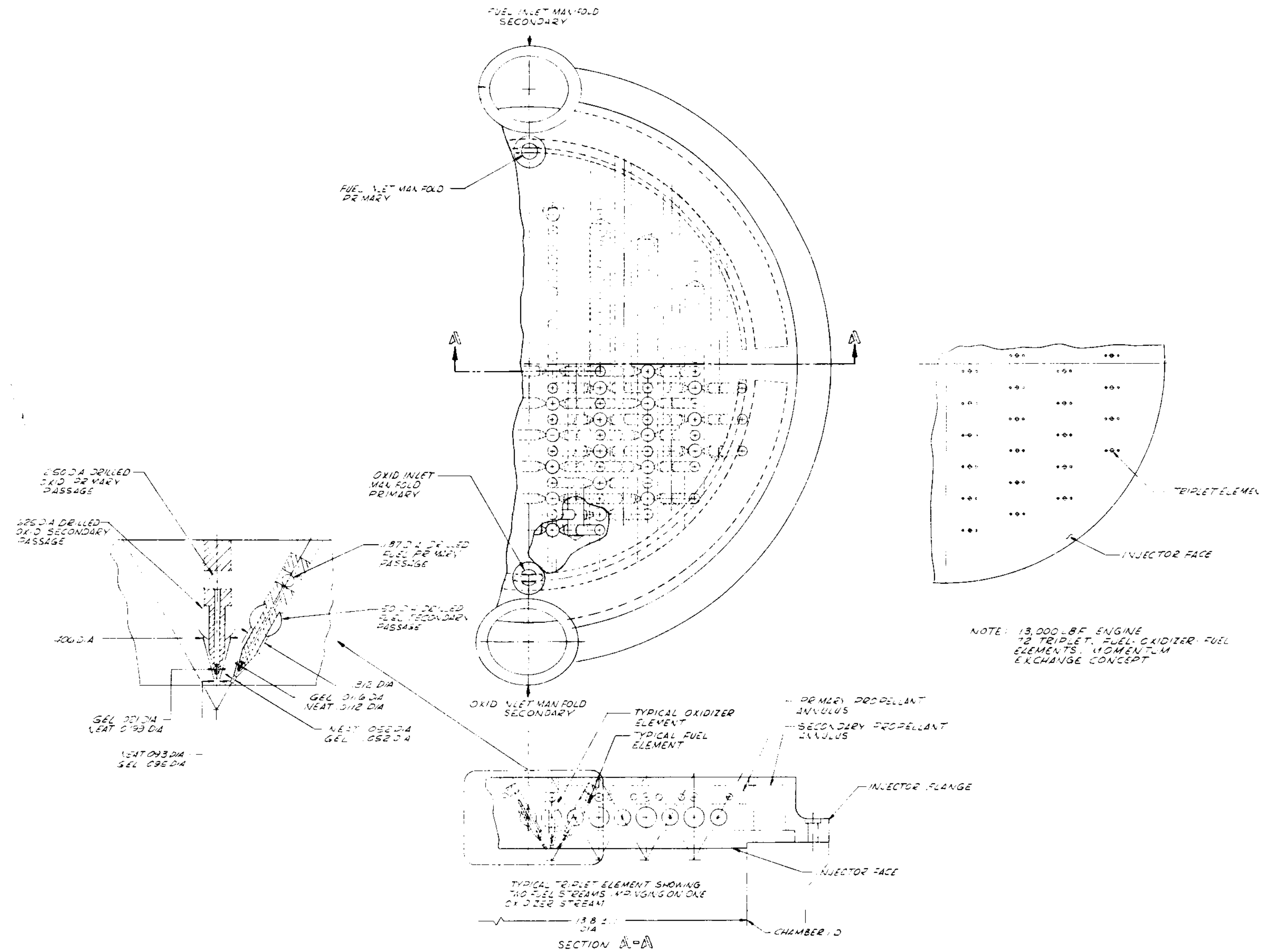
Resultant Velocity for Neat OF_2/MMH

Figure 58



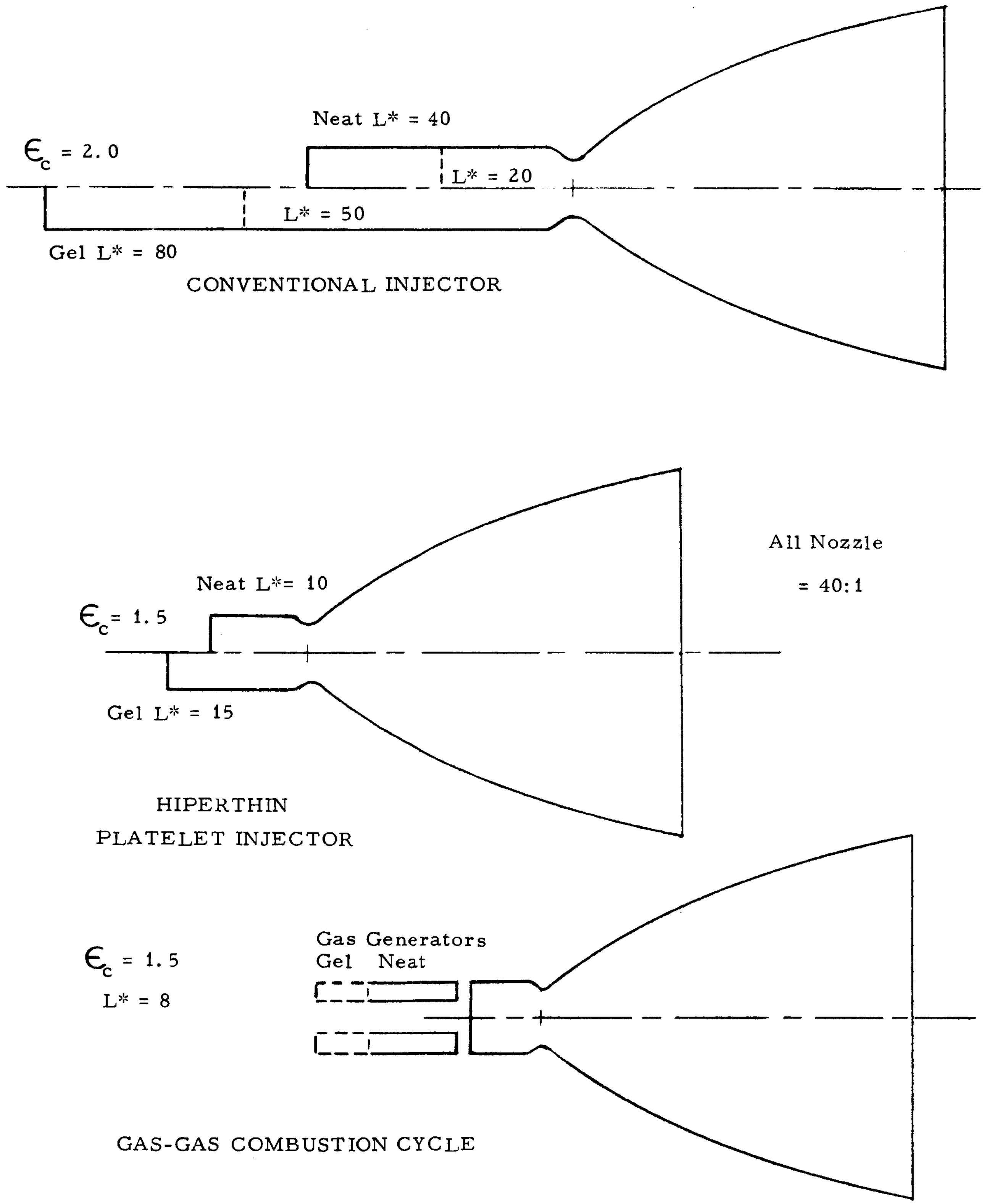
Resultant Velocity for Gelled OF_2/Gelled MMH

Figure 59



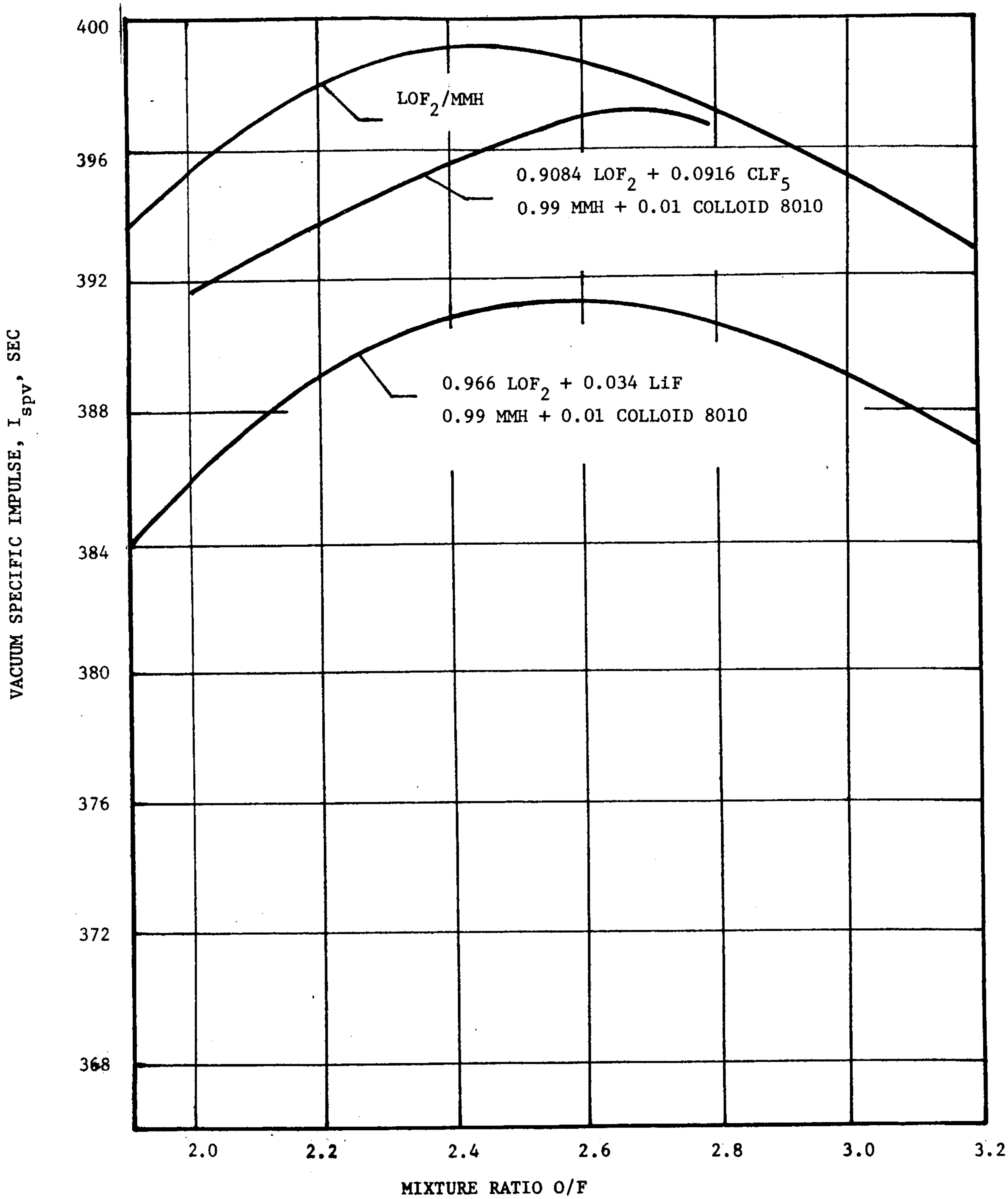
Momentum Exchange Injector, Nominal 13,000 lbf Descent Engine

Figure 60



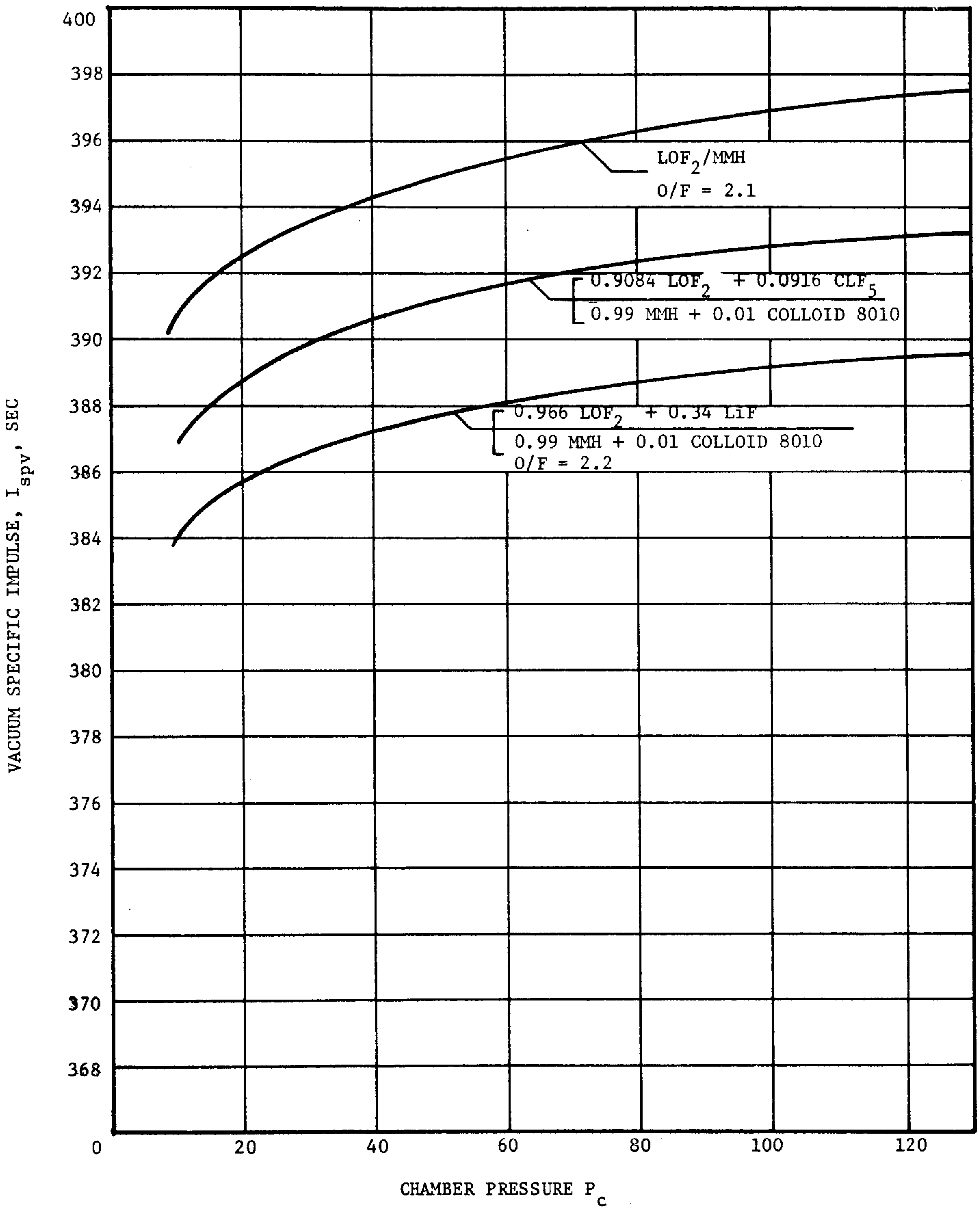
Interior Contours for 2670 lbf Thrust Chambers

Figure 61



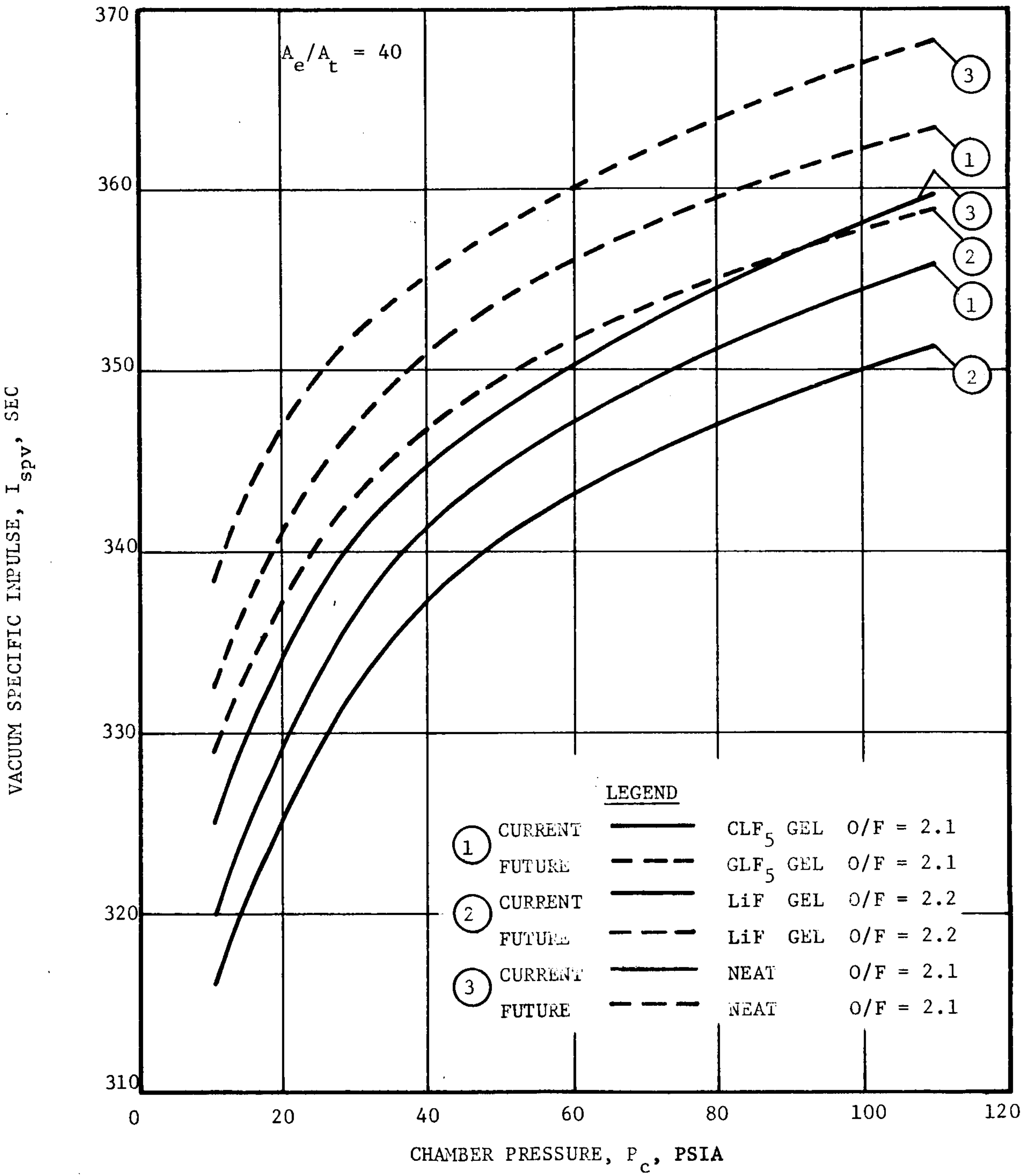
Neat and Gelled OF_2/MMH Theoretical I_s vs Mixture Ratio

Figure 62



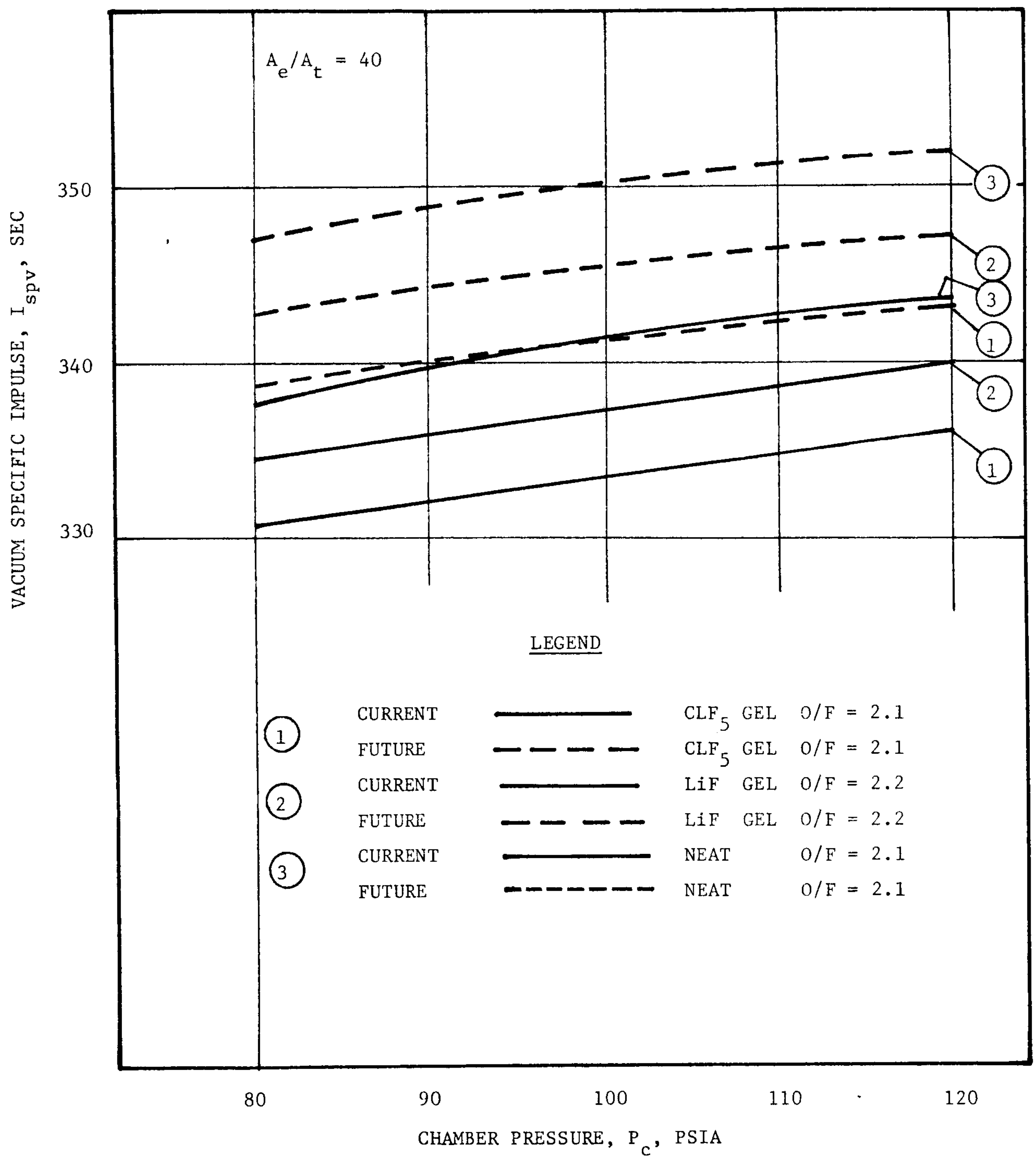
Neat and Gelled OF_2/MMH Theoretical I_s vs Chamber Pressure

Figure 63



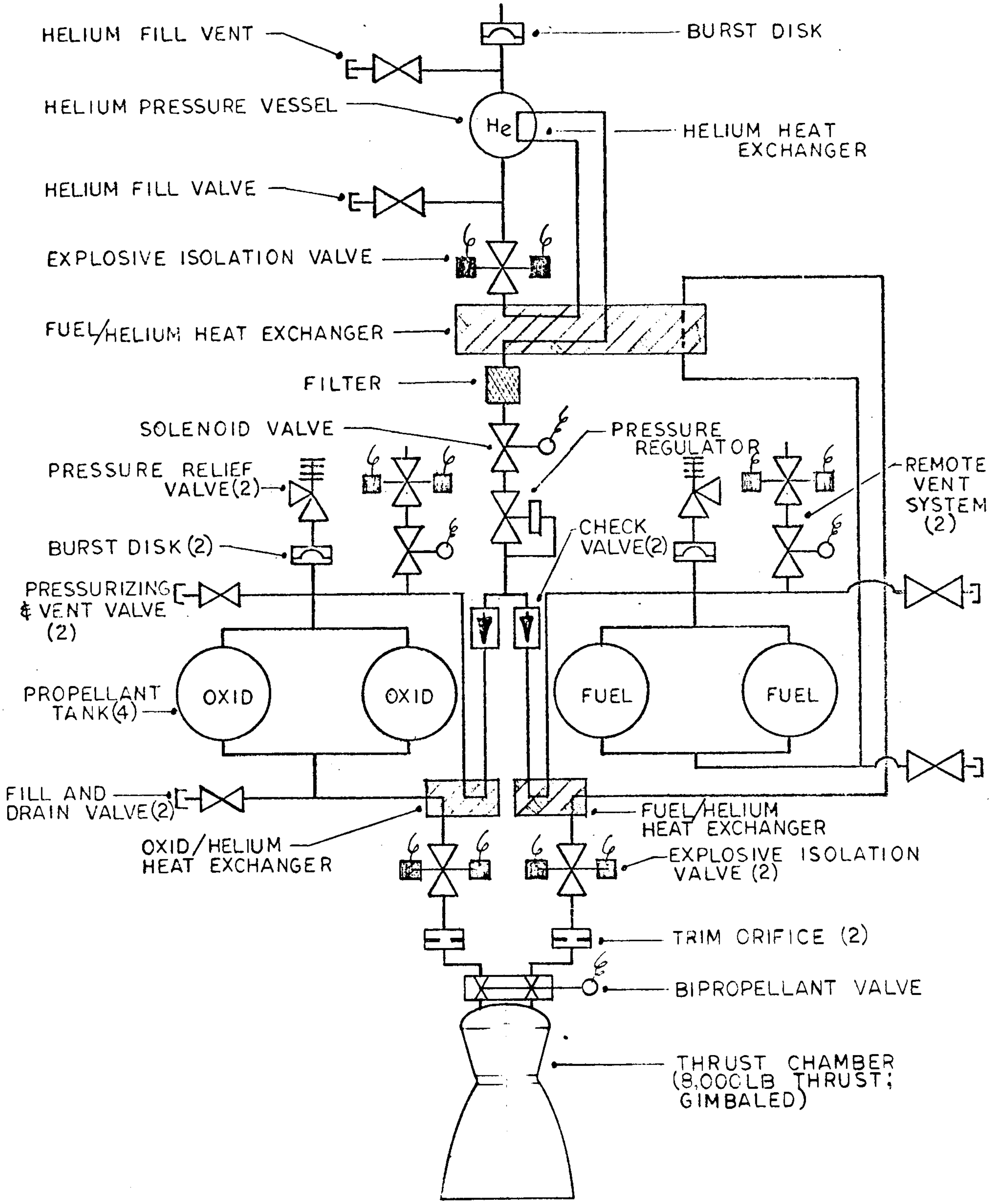
Neat and Gelled OF_2/MMH Predicted I_s vs P_c, 13,000 lbf

Figure 64

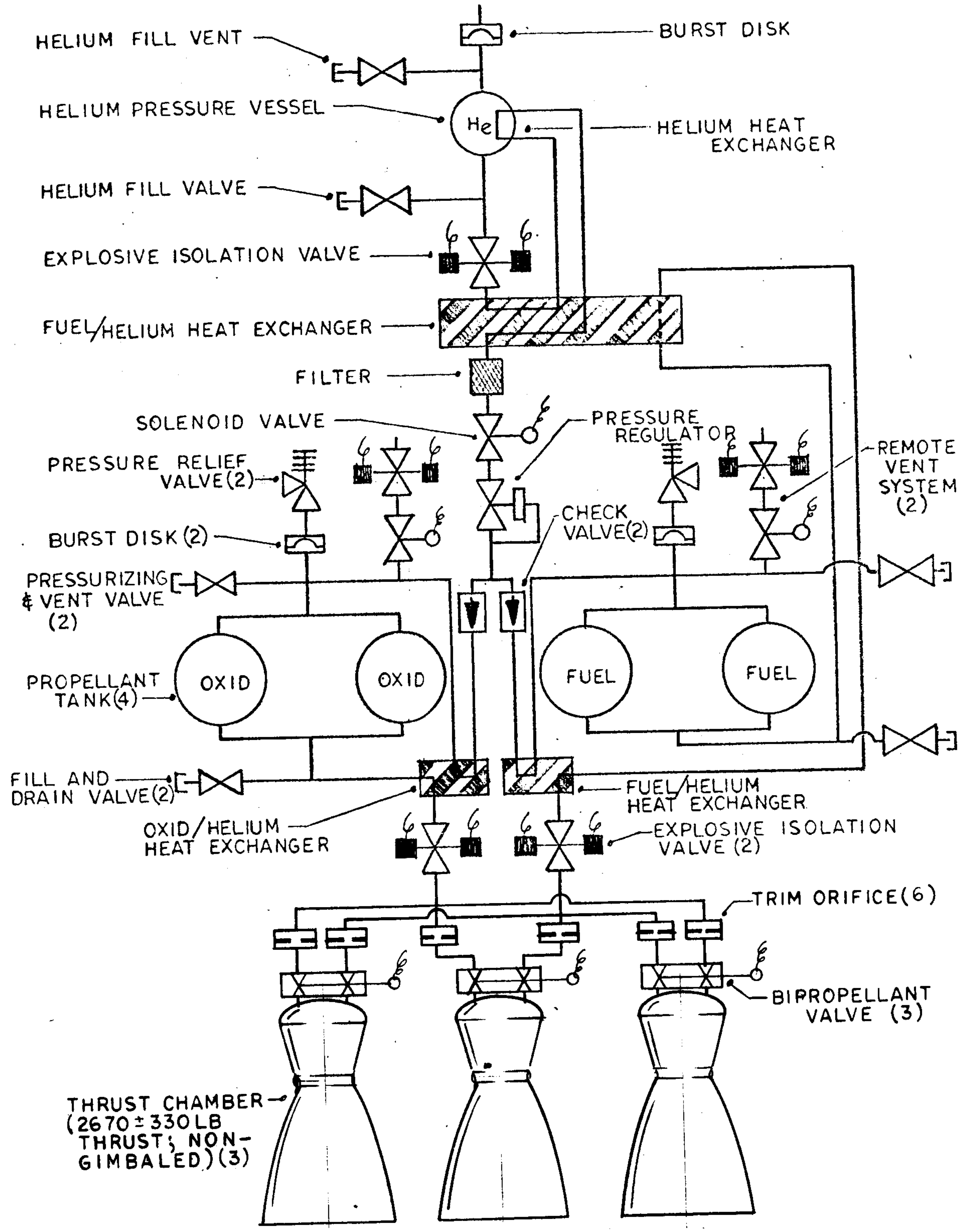


Neat and Gelled OF_2/MMH Predicted I_s vs P_c, 2670 lbf

Figure 65

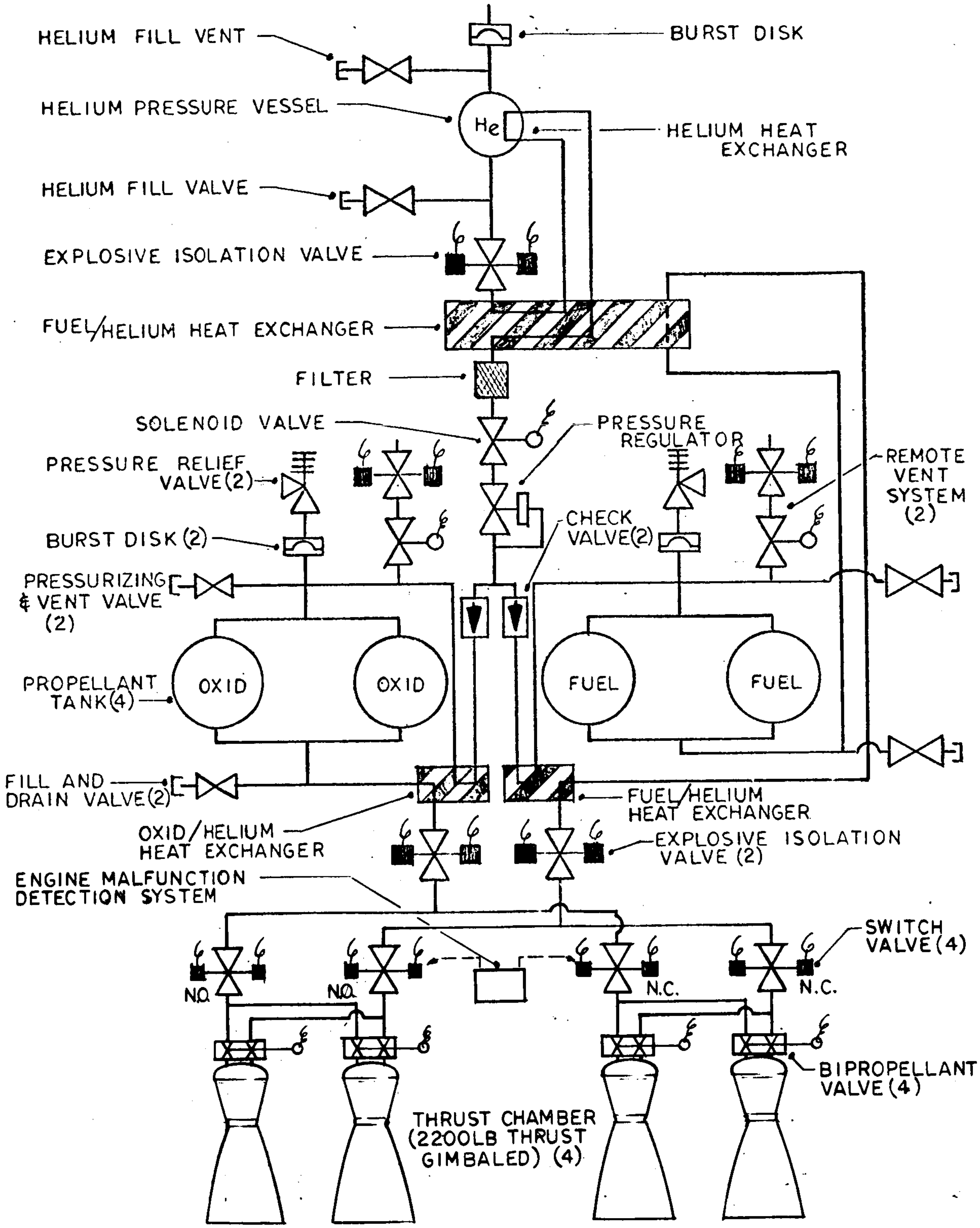


Space Probe Propulsion System (Single Chamber)

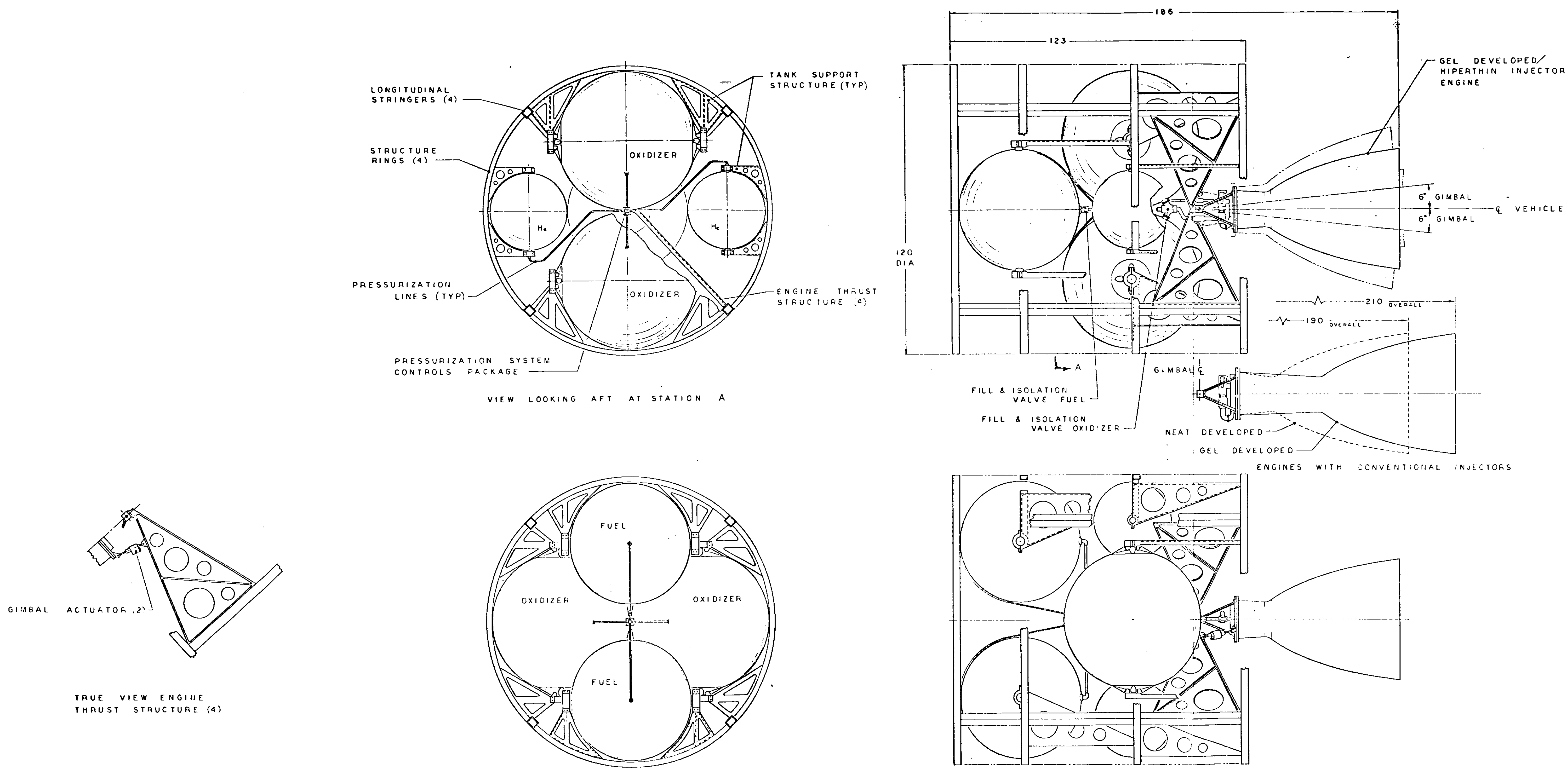


Space Probe Propulsion System (Three Chambers)

Figure 67



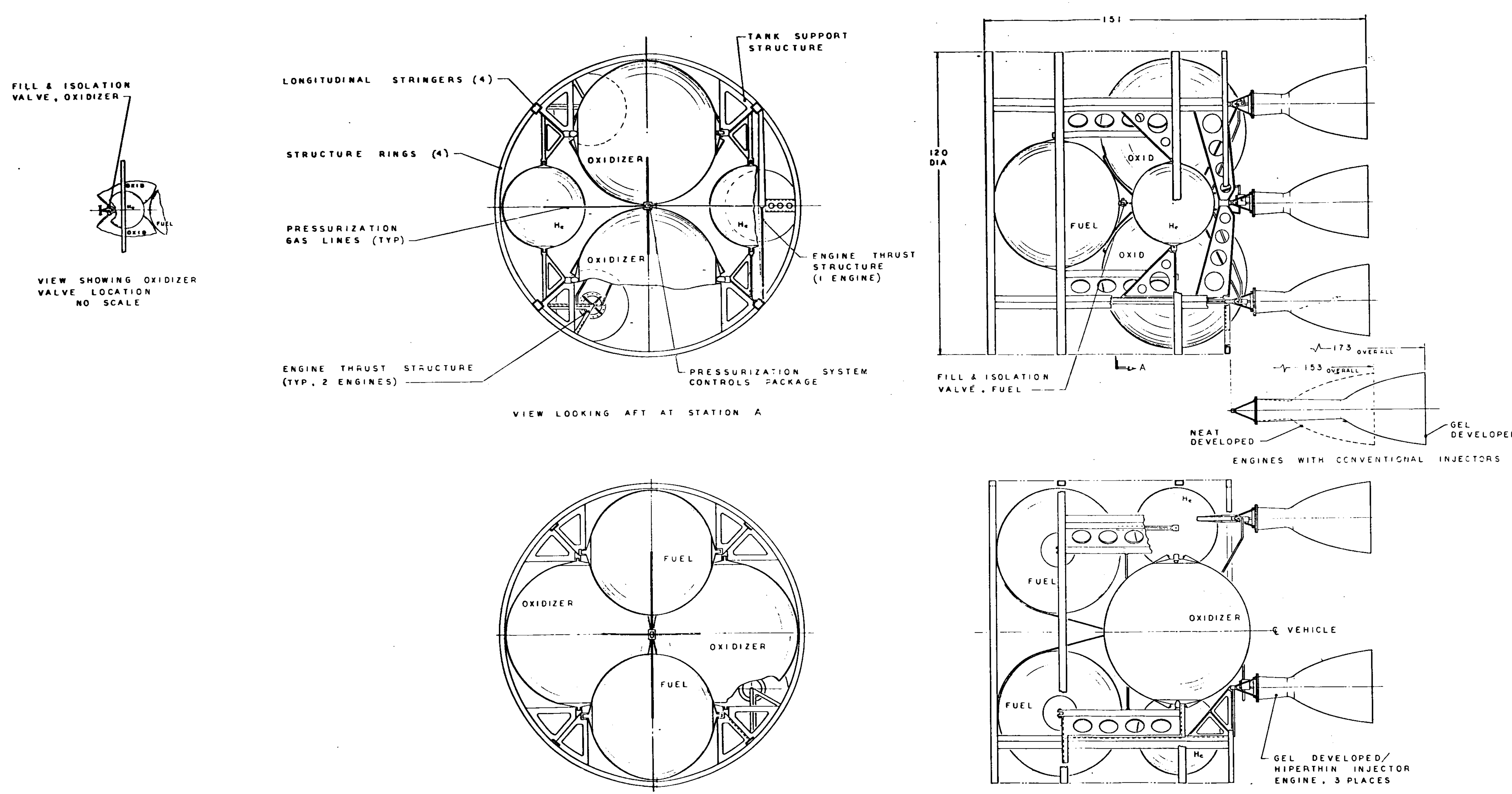
Space Probe Propulsion System (Four Chambers)



Space Probe Propulsion System (8K Single Engine Configuration)

Figure 69-2

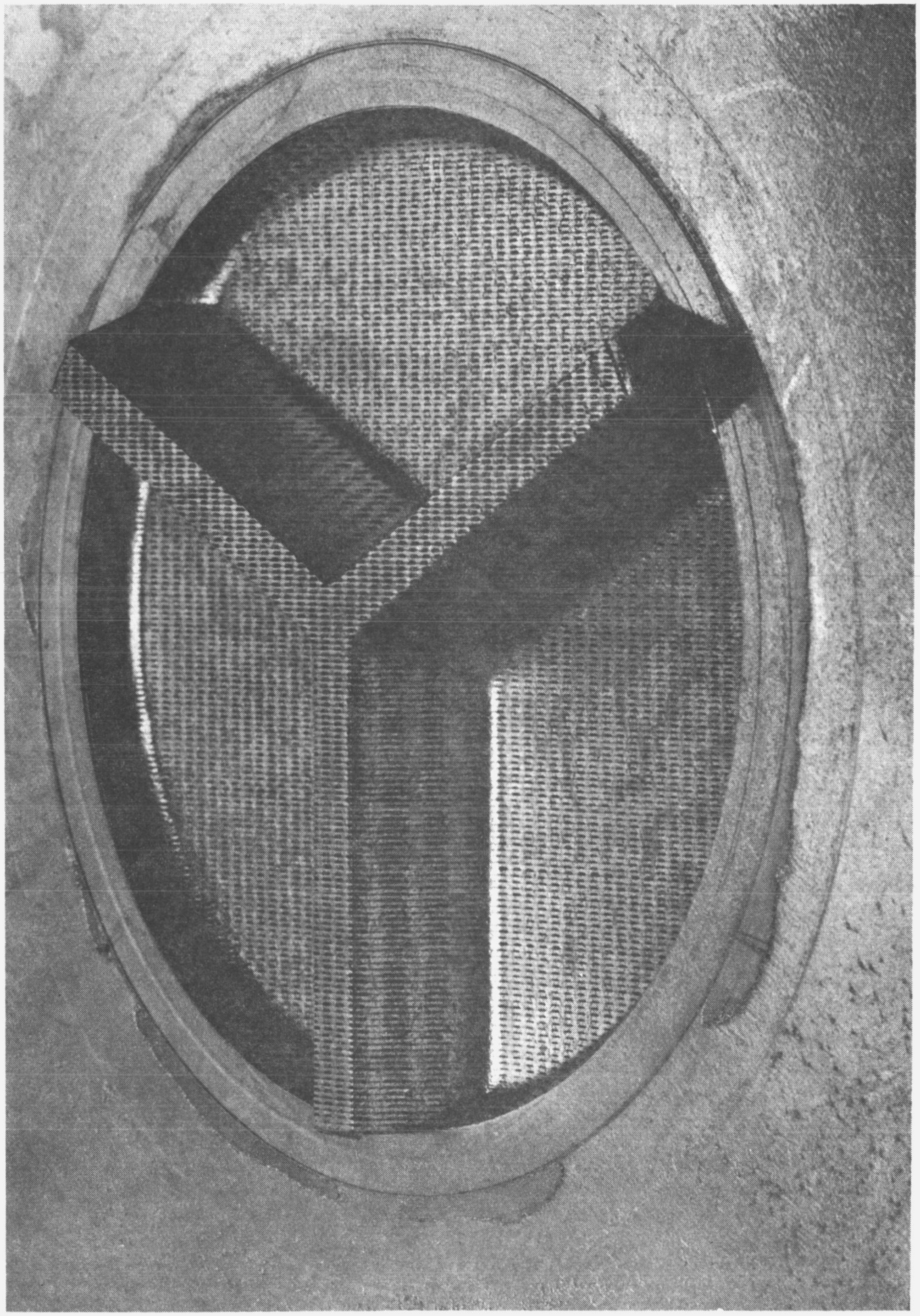
69-1



Space Probe Propulsion System (Three Engine Configuration)

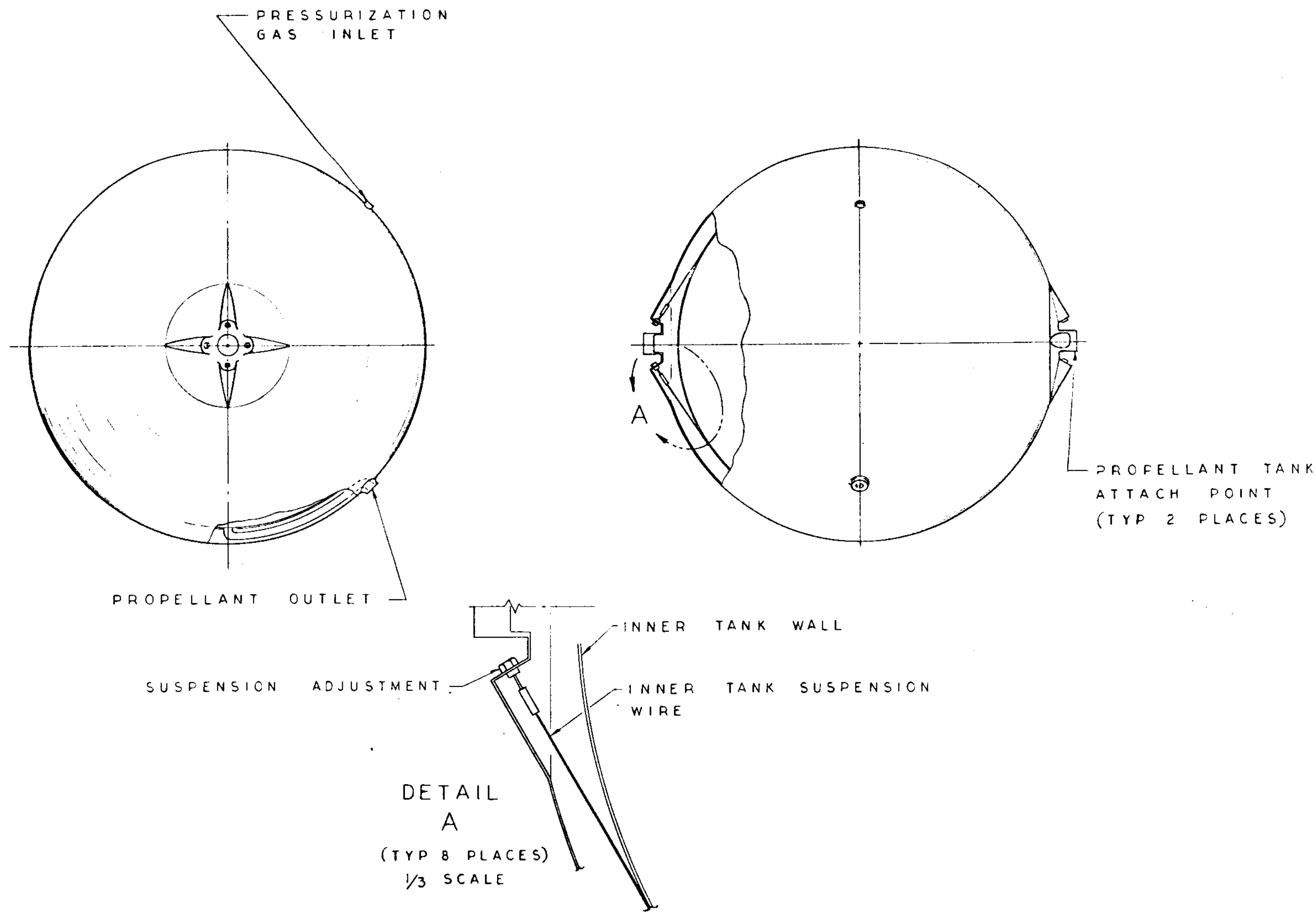
Figure 70 - 2

70-1



HIPERTHIN Injector Face with Radial Baffles

Figure 71



Oxidizer Tank for Space Probe Propulsion System

Figure 72

APPENDIX A

A GLOSSARY OF RHEOLOGICAL TERMS

(Also published ASTM D 2507-66T, 21 January 1965, and by CPIA as Part I, Heterogeneous Propellant Characterization, Liquid Propellant Test Methods, March 1967)

Adopted by The ICRPG Working Group on Liquid Propellant Test Methods

Appendix A

INTRODUCTION

The purpose of this glossary is to introduce uniformity to the nomenclature used by the propellant industry in the description of non-Newtonian propellants. Today, professional rheologists still do not agree on a set of uniform definitions, and consequently, there exists a diversity of terms which describe the same phenomena. Likewise, it is not uncommon to find a single term generally used to describe more than one phenomenon.

To promote uniformity for the purpose of effecting better communication, the Gel Test Methods Sub-Committee of the ICRPG Working Group on Liquid Propellant Test Methods has assembled the following glossary of rheological terms and recommends its use by the propellant industry.

At the time of the preparation of this glossary (December 1964), the subcommittee consisted of the following members:

Mr. J. Bost (Chairman)--Aerojet General Corp.
Mr. A. Beerbower--Esso Research
Dr. C. Grelecki--Thiokol Chemical Corporation
Dr. D. McKinney--Technidyne
Dr. A. Tarsey--Rocketdyne

Appendix A

GLOSSARY OF RHEOLOGICAL TERMS

A. CLASSIFICATION OF FLUIDS

Class I. Newtonian Fluid

A Newtonian fluid is one that exhibits a direct proportionality between shear stress and shear rate in the region of laminar flow. The shear rate is independent of the time of application of shear stress.

Class II. Non-Newtonian Shear-Thinning Fluid

A non-Newtonian shear-thinning fluid is one in which the shear stress is not directly proportional to the shear rate and in which the shear stress-shear rate ratio decreases as the shear stress increases.

Type a. Plastic Fluid

A plastic fluid is a Class II fluid that exhibits a change in shear rate directly proportional to the change in shear stress above the yield stress.

Type b. Pseudoplastic Fluid

A pseudoplastic fluid is a Class II fluid that exhibits a shear stress-shear rate ratio that is independent of the duration of application of shear stress.

Type c. Thixotropic Fluid

A thixotropic fluid is a Class II fluid that exhibits time-dependent, reversible changes of the shear stress-shear rate ratio. The ratio decreases asymptotically with duration of shear.

Appendix A

Class III. Non-Newtonian Shear-Thickening Fluid

A non-Newtonian shear-thickening fluid is one in which the shear stress is not directly proportional to the shear rate and in which the shear stress-shear rate ratio increases as the shear stress increases.

Type a. Dilatant Fluid

A dilatant fluid is a Class III fluid that exhibits a shear stress-shear rate ratio that is independent of the duration of application of shear stress.

Type b. Rheopectic Fluid

A rheopectic fluid is a Class III fluid that exhibits time-dependent, reversible changes of the shear stress-shear rate ratio. The ratio increases asymptotically with duration of shear.

B. LIST OF DEFINITIONS

I. Yield Stress

The yield stress is the maximum shear stress that can be applied without causing permanent deformation.

II. Viscosity

The viscosity is the ratio of shear stress to shear rate. For non-Newtonian fluids, it is preferable to report shear stress and shear rate. If the viscosity of such a fluid is reported, the shear rate must be specified.

III. Apparent Viscosity

The apparent viscosity of a non-Newtonian fluid is the viscosity of a Newtonian fluid that produces the same reading in the same apparatus under identical conditions.

IV. Gel

A gel is a liquid containing a colloidal structural network that forms a continuous matrix and completely encloses the liquid phase. A gel deforms elastically upon application of shear forces less than the yield stress; at shear forces above the yield stress, the flow properties are principally determined by the gel matrix.

V. Emulsion

An emulsion is a two-phase liquid system in which small droplets of one liquid (the internal phase) are immiscible in and are dispersed uniformly throughout a second, continuous, liquid phase (the external phase).

APPENDIX B

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